Exploration of **Neighboring Planetary**
Systems (ExNPS)

Mission and Technology Road Map

Presentation to the Townes Blue Ribbon Panel

October 5/6, 1995
(Revision A- October 20, 1995)
(Revision B--November 27, 1995)
ExNPS Integration Team

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Objective

◆ Develop a long term road map to:

"... to explore (i.e., to detect and study) neighboring planetary systems and to characterize and image individual planets in {hose systems"

Study Charter (1/13/95)

Agenda
Thursday Morning, October 5

8:45	Welcome	E. **Stone**
8:50	Introductory Remarks	C. Townes
9:00	Introduction (30 min.)	Elachi
9:30	The Formation of Stars and Planets (30 min.)	Boss
10:00	The Instrumental Challenge (40 min.)	Brown/Leger
10:40	Break	
11:00	The Space IR Interferometer (60 min.)	Angel
12:00	Lunch	
1:15	Technology Challenges (30 min.)	Tenerelli

Agenda (cent'd)
Thursday Afternoon, October 5

|		
1:45	Ground-based Element (45 min.)	Tytler
2:30	Supporting Space Missions (30 min.)	Beichman
3:00	Break	
3:30	Road-Map and Summary of Discoveries	Elachi
4:00	implications of ExNPS (30 min.)	Dressler
4:30	Recommendations (30 min.)	Elachi
5:00	Executive Session	
5:30	End of Day 1	
6:30	Reception and Dinner at Athenaeum (Blue Ribbon Members and Speakers)	

Agenda (cent'cl)
Friday, October 6

8:30	Discussion	
10:15	Break	
10:30	Outreach, Education, Advocacy (30 min.)	Brown
11:30	Executive Session	
12:30	1 milch	
1:15	Lab Visits (optional)	

- Micro Precision Interferometer Testbed
- Infrared Telescope Technology Testbed
- Interferometer Laboratory

Road Map 1 Development Approach

- HQ Requested JPL/Elachi to develop a road map and to have it evaluated/modified by a Blue Ribbon Panel/Townes
- JPL formed a JPL/STScI Team (C. Beichman) and two competitively selected Teams (R. Angel and R. Reasenberg) to independently develop and assess key elements of such a Road Map
- The above inputs were integrated into a single road map by an integration team consisting of researchers from universities, industry and federal labs
- [4] This draft road niap is being presented today for review/ evaluation/ modification by the Blue Ribbon Panel
- This activity involved 135 researchers from 53 Universities / Companies

Road Map Development Approach
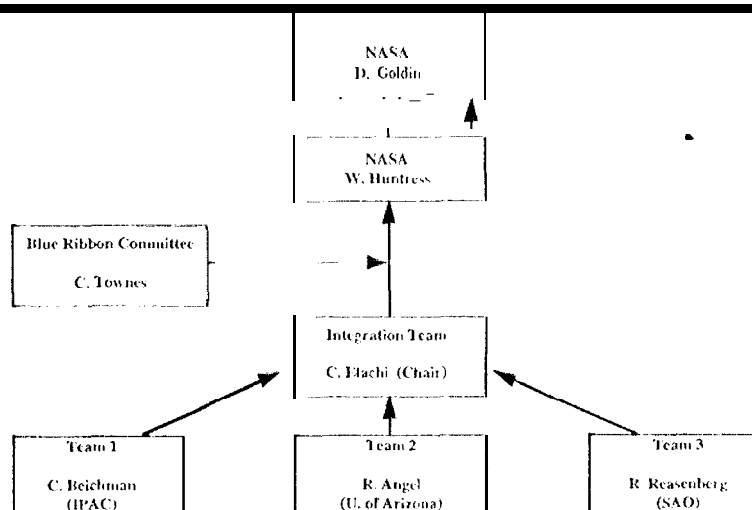
Road Map integration 'J 'cam

• Charles Elachi (Chair)	JPl
• Roger Angel	University of Arizona
. Chas Beichman	Infrared Processing & Analysis Center
• Alan Boss	Carnegie Institution
• Robert Brown	Space Telescope Science Inst
• Alan Dressler	Carnegie Observatory, Pasadena
. Freeman Dyson	Institute for Advanced Studies
• James Fanson	JPl.
• Christ Ftaclas	Hughes Danbury Optical Systems
• Lawrence Goad	Itek Optical Systems
• Mike Klein	JPL.
• Alain Leger	University of Paris
• Charles Lillie	TRW
• Stan Peale	UCSB
• Deane Peterson	SUNY-Stony Brook
• Bob Reasenberg	Harvard-Smithsonian
. David Sandler	Thermo Trex
• Mike Shao	JPl
• Richard Simon	NRAO
. Domenick Tenerelli	Lockheed-Martin
• David Tytler	UCSD

Key Guidelines from NASA 11Q

* To explore and characterize planetary systems around the neighboring few thousand stare with the ultimate goal of imaging Earth-like **planets**

* Develop a streamlined road map with specific focus of **direct detection and spectral** characterization

* Develop road map with a continuous **flow of scientific discoveries and technological advances vs. a** single **event in the far future**

* Develop **a road map** that capitalizes on other planned activities such as SIRTF, HST, AIM, HST **follow-on, etc.**

* **Road map** should cover missions, **technology** and ground observations

* Explore **every** possible technology

+ Be visionary but fiscally realistic

## Some Recent History of the Program

+ 1978   **"NASA Workshops cm** Ground-Based Techniques **for** Detecting Other Planetary **Systems",** 1). C. Black **(1980)**

* 1984   L. **Allen (**JPL Director**) selects** extrasolar **planetary** detection **as a key objective of** JPL Director Discretionary Fund

+ 1988   **NASA forms 'T'01'S (**Toward **Other** Planetary **Systems)** Working Group Chaired by B. Burke

* 1989   **NASA starts** Origins SRT Program

* 1990   NRC-Complex Report on "Other **Planetary systems"**

+ 1992   TOPS Report issued

## Some Recent History of the Program
(Cent'a)

- ◇ 1993   NASA approves Palomar interferometer development as a test bed for eventual Keck interferometer

- ◇ 1993/94   D. Goldin challenges the NASA science/ technology community to develop the capability to explore neighboring solar systems

- ◇ 1994   NASA signs cooperative agreement with CARA to become 1/6 partner in Keck Observatory with the explicit objective of supporting TOPS research. Long term objective to couple Keck I and II as an interferometer

- ◇ 1994   NRC-Complex Report recommended intensive search for extrasolar planets as key program

- ◇ 1995   NASA requests JPL to work with the community to develop the road map

Key Findings of What Can be Done
In the Foreseeable Future (10 to 20 years)

- ◇ **Acquire "family portraits" of 150-200 possible planetary** systems in our neighborhood **of** 13 pc (**-42** ly) sphere **(1 000** stars)
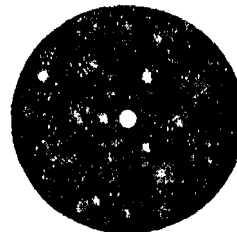

- ◇ Characterize spectra of the **brightest 50-1 00 of** the detected planetary **systems.** Identify Earth-like **planets**
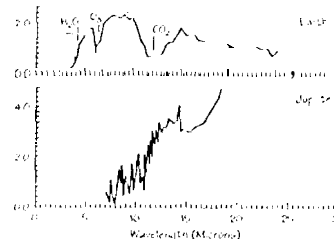
Key Findings of What Can be Done
### Near Term Scientific Opportunities (1-0 years)

⬦ Indirectly detect planets from Jupiter to Earth masses
  - Ground-based techniques
    - Radial velocity and astrometric measurements to Uranus mass
    - Microlensing detection of Earth masses
  - Space-based techniques
    - AIM can extend ground-based astrometry to lower mass and more stars
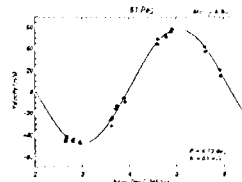
⬦ Characterize debris-disks/zodiacal-systems around nearby stars
  - ISO/SIRTF measurements
  - Ground-based interferometers
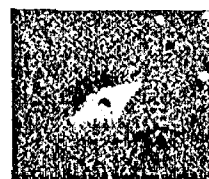
⬦ Directly detect giant planets around nearest stars
  - "Super"-Adaptive Optics on large 6-10 m telescopes
  - Balloon, HST coronagraph

Key Findings of What Can be Done
In The Near Future (1-10 years)

⬦ A robust **program** in advance **of major space mission will** answer key **scientific questions:**
  - Frequency of planets of various masses
  - Brightness of zodiacal clouds around other stars
  - Further understanding of planetary formation

⬦ Such a program will enable frequent discoveries to maintain scientific, technical, public interest

⬦ **NASA has opportunity to** enable dramatic **advances in** detection of **planets**
  - Years of low-level funding (NSF, University, . . .) set stage for new discoveries

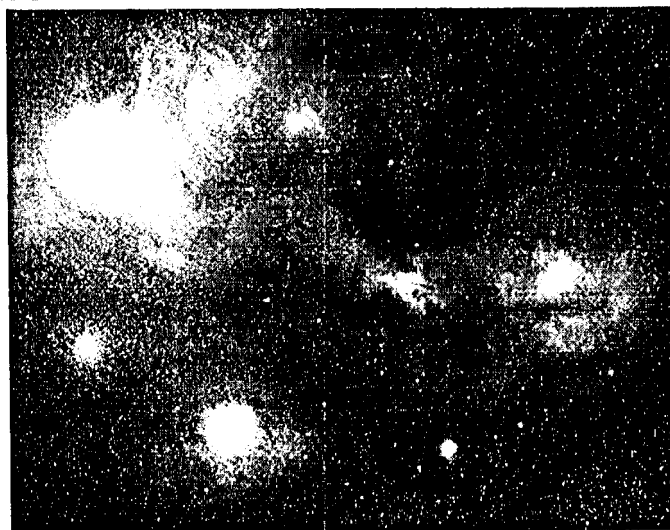⬦ Interferometry and **associated technologies are** central for achieving ExNPS **objective**

Key Findings (Technology)

◆ The technology to construct such a program is very challenging but within our reach in the next decade

◆ SIRTF will demonstrate key technologies and provide critical data on exo-zodiacal light

◆ AIM, with the appropriate configuration, could demonstrate critical technologies for the full-up ExNPS interferometry concepts

◆ An expanded NASA space interferometry technology program would address all the needed technologies within the next decade
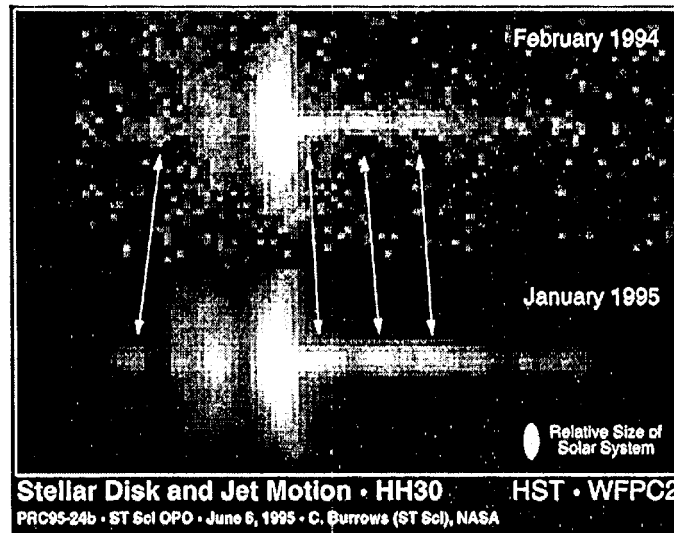
The Formation of Stars and Planets

Alan Boss
Carnegie Institution

Rho Ophiuchus

Stellar Disk and Jet Motion

Stellar Disk and Jet Motion • HH30 — HST • WFPC2
PRC95-24b • ST ScI OPO • June 6, 1995 • C. Burrows (ST ScI), NASA

Modern Era of Planet Formation Theory

AKADEMIYA NAUK SSSR
INSTITUT FIZIKI ZEMLI IMENI O. Yu. SHMIDTA

Academy of Sciences of the USSR
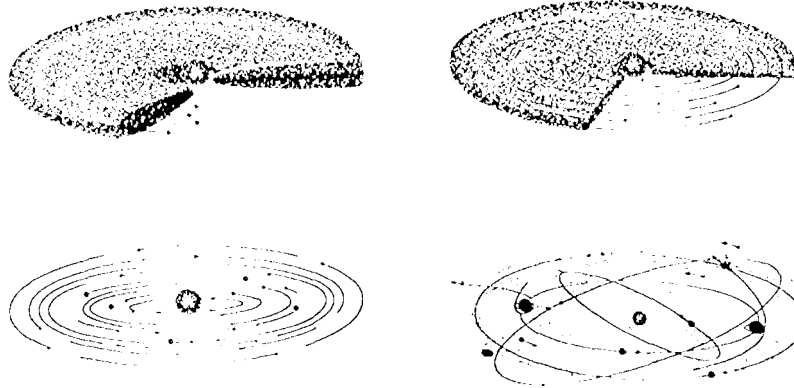Shmidt Institute of the Physics of the Earth

V. S. Safronov

EVOLUTION OF THE
PROTOPLANETARY CLOUD
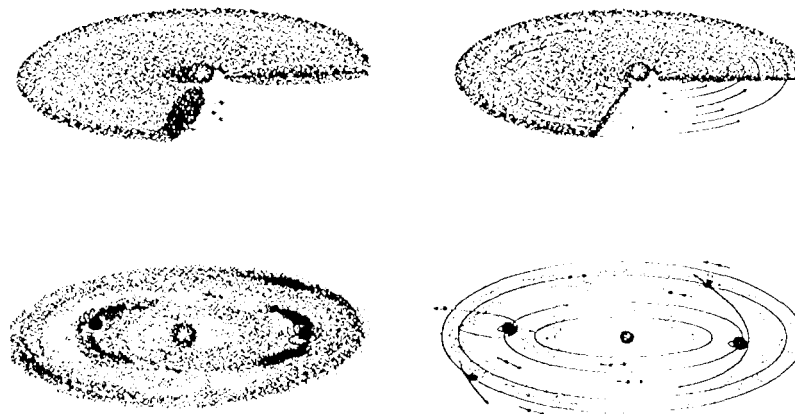AND FORMATION OF THE
EARTH AND THE PLANETS

(Evolyutsiya doplanetnogo oblaka i obrazovanie Zemli i planet)
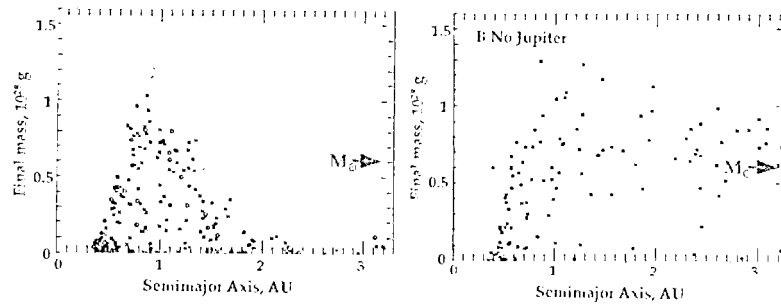
Izdatel'stvo "Nauka,"
Moskva, 1969

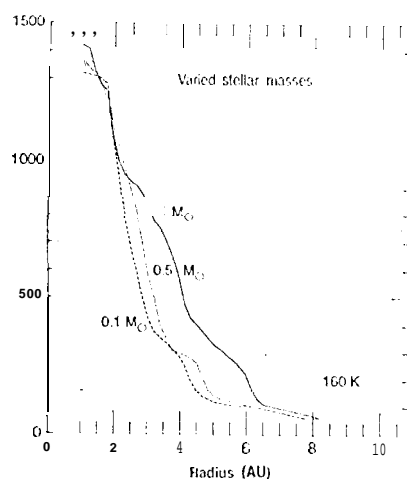## Sequence of Events in
Terrestrial Planet Region

Sequence of Events in
Giant Planet Region

# Collisional Accumulation in the inner Solar System

Three Protoplanetary Disk Models

Some Key Questions for the Theory of Planetary Formation

* How prevalent are planetary systems like our own? Is there any reason to believe that the formation of our solar system was unusual?

* Are Jupiter-mass planets rare? Do protoplanetary disks generally dissipate prior to giant gas planet formation?

* Are Neptune-mass and Earth-mass planets common? Does planetesimal accumulation inevitably lead to the formation of rocky inner planets like Earth and icy outer planets like Neptune?

* Can planets be detected in binary or multiple stellar systems? On what orbits do they occur?

* What are the physical properties (e.g., density, temperature) of protoplanetary disks? How do they evolve? How do they dissipate?

Post-Fit Residuals of Pulse Arrival Times
Pulsar PSR B 1257+12
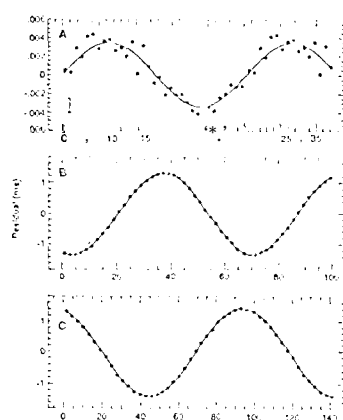
Planet Mass ($M_\oplus$)	Distance From Pulsar (AU)	Orbital Period (days)
0.015/sin i_1	0.19	25.34
3.4/sin i_2	0.36	66.54
2.8/sin i_3	0.47	98.22

Circumstellar and Debris Disks
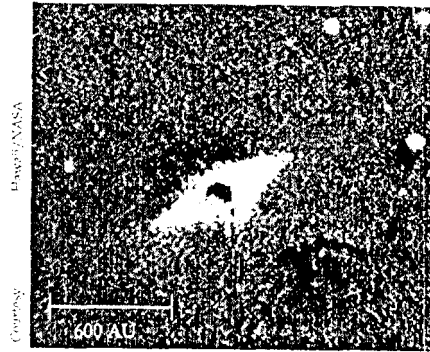
Particles around β Pictoris.
These particles are the source
of exo-zodiacal emission
which can be brighter than
planets in the infrared.
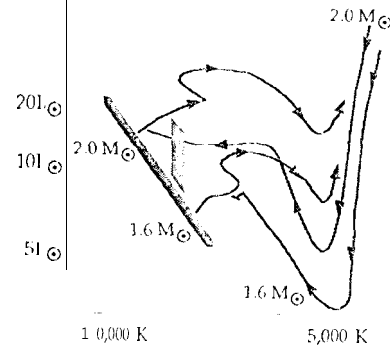
The Hertzsprung-Russell diagram
estimates the age of β Pictoris.

The Instrumental Challenge

Robert A. Brown
Space Telescope Science Institute
and
Alain Léger
University of Paris

Introduction

- ◇ ExNPS program will decisively address two outstanding issues left over from the Copernican Revolution of 500 years ago:
    1. What is the Solar System's place among planetary systems around other stars?
    2. Are there other worlds like Earth?

- ◇ The ExNPS ground-based program addresses Issue 1, as well as the existence of Earth-mass planets

- ◇ The ExNPS space-based program addresses Issue 2, the plurality of worlds

Overview

◆ This presentation provides the **basic concepts for the ExNPS program**

- **What stellar** population **is** being targeted?

  1000 stars within about 13 parsecs or 42 light years

- What is a planet?

  mass, and orbit

- Wha[is an larlh-like planet?

  mass, size, atmosphere

- What are the signals from planets, the techniques to observe them, and the information they convey?

  effects on the star (indirect techniques)

  planetary radiation (direct techniques)

1000 Stars

◆ The **nearest 1000** stars **comprise** the **primary** search space **for planets**

- * Largest astrometric displacements

- Greatest separations for direct imaging

- Most light for direct imaging and radial velocity measurements

◆ 315 known stars within 10 pc **(13 new since 1991; 24 candidates in 1995)**

- 4 **A** stars, 6 F stars, 22 G stars, 47 K stars, 219 M stars, 17 white dwarfs

- **60%** of G stars and **40%** of M stars are in binary systems with solar-system-scale orbits

- **226** stellar systems

1000 Stars (cont'd)

◆ **The inventory of stars is incomplete** beyond 5 pc
  - Estimate 130 "missing" systems within 10 pc, mostly M dwarfs
  - **With** multiplicity, expert 500 stars in 10 pc or 1000 within 13 pc

◆ The 1000 **nearest** stars **have a special place, and** should be **studied intensively** to determine their peculiar **properties as** they **may** influence **and inform** planetary searches
  - Ages (luminosity of cooling gas giant planets)
  - Stellar activity (velocity fields ant] photocenter displacement)
  - Rotation periods (inclination 10 the line-of-sight)
 - Circumstellar dust (exo-zodiacal emission)

1000 Stars (cont'd)

What Is A l'lane{?
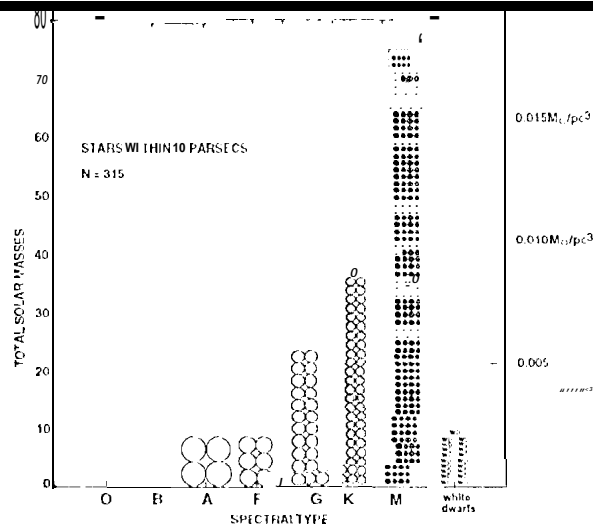
◆ The genetic definition of "planet" is the most scientific: a planet is any object that forms by accretion in a circumstellar disk

◆ **Circular**, coplanar orbits are the **signature** characteristic of planetary systems.
   ⌙ Due to viscous damping of eccentricity in the protoplanetary disk

◆ **All ExNPS** search **techniques** except the microlensing survey- -direct and **indirect**- will **determine** orbital **shapes, orientations,** and **alignments to certify "planetary"** status

◆ If orbit is circular, the object is a presumptive planet

Pl anetary Systems

◆ Other planetary systems should be flat and circular like the Solar System. This is because the viscosity of the protoplanetary disk should damp eccentric, inclined orbits.

◆ Multiple star systems- including brown dwarf companions- display a wide range of eccentricity.

◆ To learn about planet forming in the general context of star formation, we must study the kinematical structure of other planetary systems.
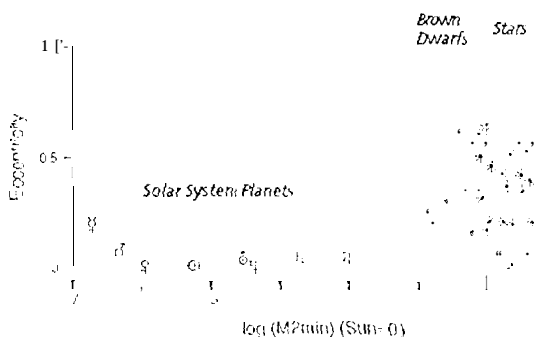
Adapt edfrom: Duquennoy, A., and Mayor, M (1990). Duplicity of Solar-Like Stars in the Solar Neighbourhood. In press in Proceedings of the XII uropean Regional Astronomy Meeting of the IAU, 1989. (I d M Vasquez; Cambridge University Press)

Planets

- Planets accrete in disks, whereas stars and brown dwarfs condense in collapsing?, molecular clouds.
- Small or mature planets, reflect star light mainly, and they are hot or cold depending on their distance from the star.
- Large gas planets (and brown dwarfs) emit excess thermal radiation due to gravitational contraction. At an early age, this class of objects can be quite luminous.

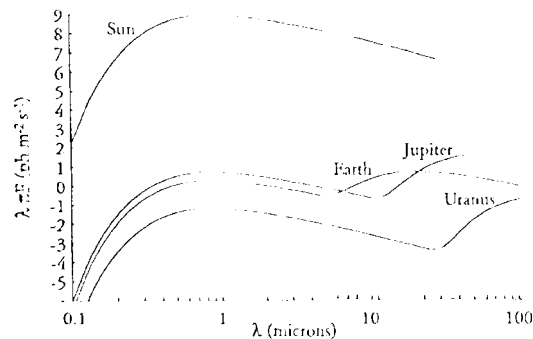---
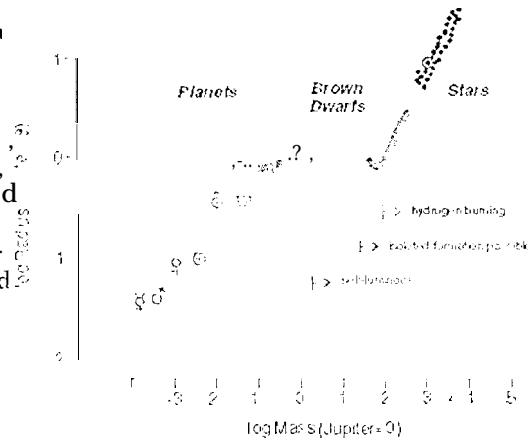
Solar System Fluxes from 10 Parsecs

- **Spectral** energy distributions **of planets have two** components
  - Reflected solar radiation:
    -stellar flux X albedo X radius^2/orbit^2
  - Thermal radiation:
    ~B (Teff, λ) X radius^2
- **Direct** detection is more **favorable in thermal than in reflected light**
  - o 1000x more favorable star/planet flux ratio

What is an Earth-like Planet?

◇ Mars, Earth, and Venus are all **"1** Earth-like"
(terrestrial) planets

- Small size and **mass compared to** gas giants
- Atmospheric mass small compared to solid body
- Solid surface
- **Various** albedos
    Mars (.17) dirt
    Earth (.35) cloud cover, oceans
    Venus (.71) cloud cover

What is an Earth-like Planet? (cont'd)

◇ Spectra provide information about atmospheric composition

- Spectra of solar system planets display wide variety
- The 10-micron spectral region is particularly diagnostic
- A resolution of 10-20 is adequate to detect carbon dioxide, ozone, water
- CO_2 says an atmosphere exists
- O_3 (ozone) indicates O_2, which begins with biological photosynthesis on Earth
- H_2O— if the planet is in the "habitable zone"— indicates liquid water
- Habitable zone defined by temperature range compatible with liquid water

What Is The, Habitable Zone?

◆ Liquid water **is** believed {0 be advantageous **for** the **emergence** of **life**

◆ **Surface temperature** between 0 and 100 C **defines habitable** zone **for 1 atmosphere surface pressure**

◆ Temperature determined 'c by balance between

- Stellar brightness
- Distance from star
- Albedo
- Strength or greenhouse effect
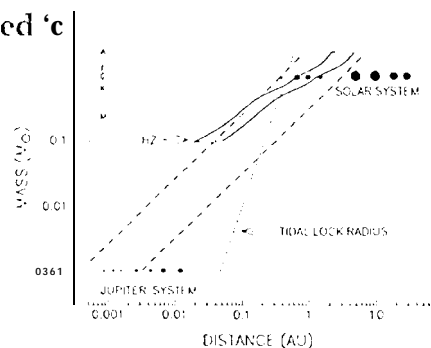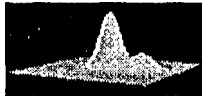
From Kasting 1994

Planetary Atmospheric Spectra
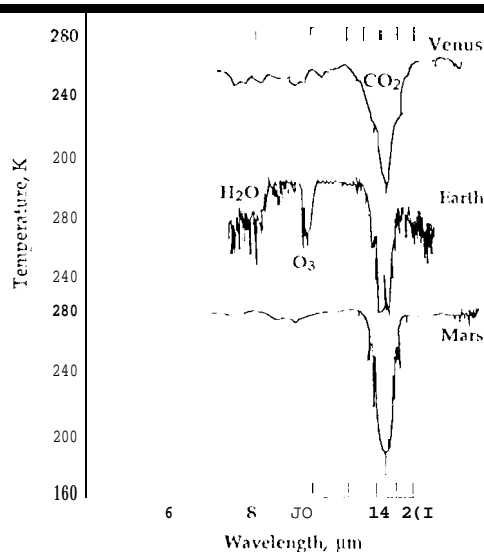
]'lane Search Methods

Class	Method	Technique	
	Astrometry	Measure wobble of star	Mass Semi-major axis Eccentricity Inclination
	Radial velocity	Detect doppler shift of stellar spectra	Mass Semi-major axis Eccentricity
Indirect	Occultations	Photometry	Semi-major axis Size
	Microlensing	Photometry	Mass Angular separation
Direct	Imaging	Visible and IR imaging of planets	Semi-major axis Eccentricity Inclination Sift Temperature (IR) Composition

Astrometry and Radial Velocity

- ◆ Astrometry and **radial** velocity record two facets Of tile same phenomenon: **the reflex motion of the star orbiting around** the barycenter
  - Both techniques can quickly discover the existence of a planetary system by detecting a simple acceleration in a fraction of an orbital period
  - Both techniques require multiple-orbit observations to disentangle a multi-planet system
- ◇ Astrometry measures the **shift in** the star position
  - With the-stellar mass (spectral type) and distance (parallax), the planet mass and semi-major axis can be computed (see graph)
  - Orbit eccentricity is also determined
  - Noise floor is set by star spots (1 micro-arcsec = 0.002 solar radii @ 10 pc)
  - More mass sensitive to wider, longer period orbits

Astrometry and Radial **Velocity** (cont'd)

◆ Radial Velocity measures the projected star orbit speed and the period
  - **inclination** must be estimated; with star mass from spectral type, the planet mass and semi-major axis can be computed
  - Orbital eccentricity is also determined
  - Noise floor is set by stellar velocity noise (1m/s = 5m p-mode and 0.1% starspot shading of rotational velocity field)
  - More sensitive to smaller, shorter period orbits

◆ Only astrometry and radial **velocity can** determine the planet mass **directly**
  - Astrometry achieves this without the ambiguity of the inclination angle
  - Radial velocity measures m/sin i

Astrometry **and Radial** Velocity (cent'cl)

◆ Earth-mass **planets around solar** type stars **are an** order **of magnitude** below the **expected stellar noise floors for both** astrometry and radial **velocity**

◆ **Ground-based observatories can exploit both** astrometry **and radial velocity to** the **stellar noise limit**
  - 1 m/s with 10-m **telescopes**
  - 100 micro-arcsec with 10-m telescopes
  - 10 micro-arcsec with 100-m baselines
  - 1 micro-arcsec with 500-111 baselines

Solar Wobble in 65 Years
(Pole-on View from 10 pc)
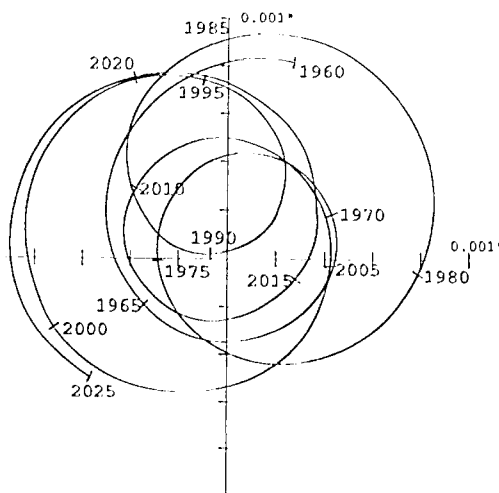
indirect 1 Detection of other 1'1 ancts

◇ Astrometric Method	◇ Radial Velocity Method
• Best for larger planets	• Independent of distance
• Decrease with distance	
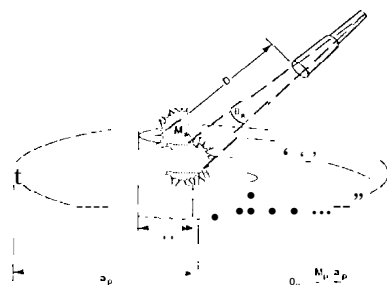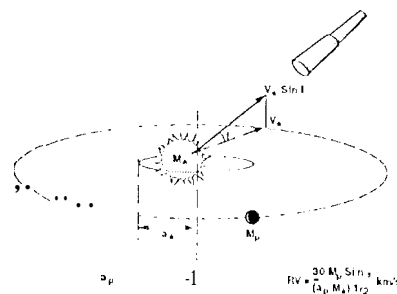
Microlensing By Star With Planet
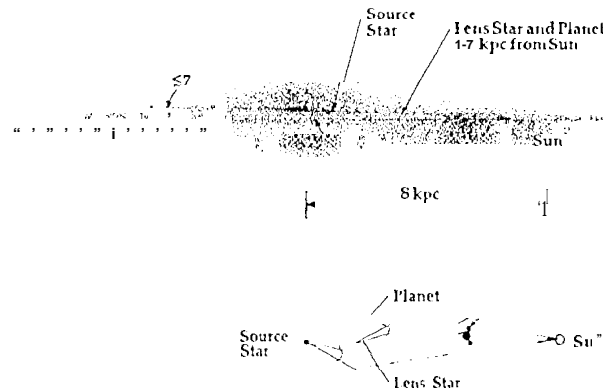
Microlensing

- ❖ Gravitational lensing is now a **familiar astronomical** phenomenon- stars, **galaxies, and clusters of galaxies, and scales ranging from galactic to cosmological**
- ❖ Star-star lensing events **are** now being observed at **a** rate of **almost 5b/year**
    - Typical amplification of 2-5 times
    - Typical duration of 40 days
    - Line-of-sight to the galactic bulge is richest in Opportunities

Microlensing (cent'cl)

◆ **secondary** events can occur due to planets **of the** lens star

- Can be a large effect even **for** low-mass planets
- Best planet position is near Einstein ring (1-4 AU)
- Occur when either of the two moving lensed images approaches the planet
- Events short (2-40 hours), complex, and spiky (due to caustics)
- Planet mass and separation can be determined from the light curve

◆ Microlensing events are one-time, no **follow-up**

◆ ExNPS microlensing survey can detect Earth-mass **planets from the** ground, before **building a space** system **capable of** imaging **them**

Theoretical Model of Lens **Star Amplification**
$(0.3M_{sun})$ Lens **Star at 6 kpc**
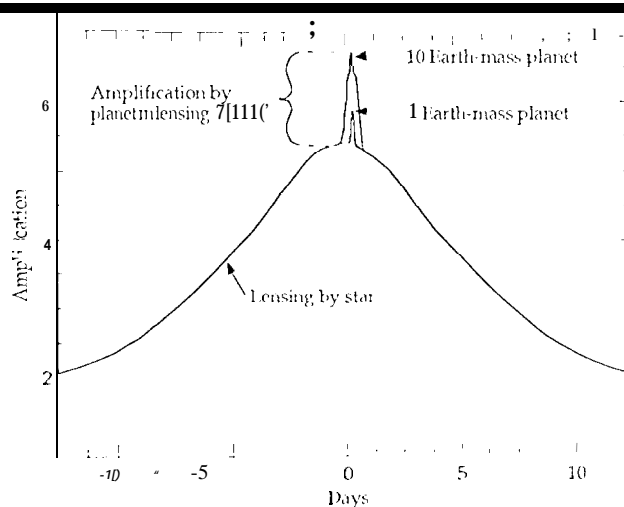
From Bennett and Rhie, 1995

Direct imaging

- ◆ Direct imaging **is the** best **pathway** to discovering then studying Earth-like planets
  - ◦ Must isolate planet light to study intrinsic properties through spectroscopy
- ◆ Unresolved (1-pixel) images of planetary systems will be exciting early results: planets shown "orrery"
- ◆ Direct **imaging systems must** have **sufficient angular resolution** to **separate the** planet **and the star**
  - ◦ For 1 AU at 10 pc, characteristic size is $(\lambda/1\mu m)$ meters
  - ◦ In the IR, break up the aperture (interferometer) because collecting area of filled aperture is not required

Direct imaging (cent'd)

- ◆ **Although planets are intrinsically faint sources, reasonable collecting areas can** detect **their** signal
- ◆ Key challenge **is star-to-planet brightness contrast**
  - $\sim 10^9$ **visible**
  - $\sim 10^6$ infrared
- ◆ High background **contrast** problem
  - • Telescope IR background, eliminated in space by cooling
  - ◦ Solar system IR zodiacal emission, escaped at 4-5 AU
  - ◦ Aberrated **starlight,** corrected by adaptive optics
  - • Diffracted star light, suppressed by Fourier techniques
  - • Exo-zodiacal emission, a poorly quantified factor

Direct imaging (cent'd)
Resolving Earth-sized Planets

◇ The **interferometer** needed to resolve an Earth-sized planet **around another star** is 10^5 times larger **than** the one needed **to** discover it

- $10^5 = 10$ pixels across diameter X ($10^1 = 1$ AU/Earth diameter)
- **1000 km baseline**
- New star nulling scheme would **need** to be invented (stellar disk resolved)
- Not ruled out by the laws of nature, but not considered feasible at the current time

---

Resolving Distant Planets

Pixel / Diameter	Pixel size @ planet (km)	Pixel angle @ 10pc (arcsec)	Image
400	82	2.1×10^{-4}	
100	128	8.5×10^{-4}	

Interferometer Requirements

	Area	Baseline
IR	144,000,0001112	300,000 km
Vis.	1,296,000,000 m²	5,000 km
11{	640,000 m²	24,000 km
Vis.	5,760,000 m²	1,200 km

Resolving Distant Planets
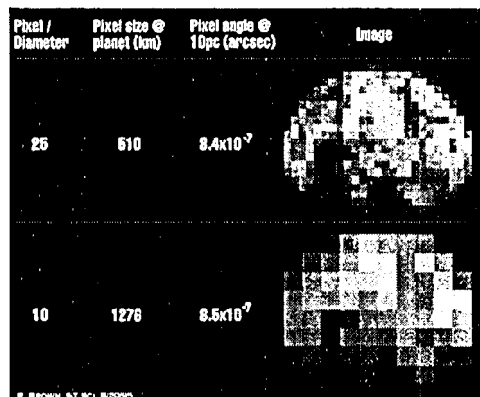
Pixel / Diameter	Pixel size @ planet (km)	Pixel angle @ 10pc (arcsec)	Image
25	510	8.4x10⁻⁹	
10	1276	8.5x10⁻⁹	

Interferometer Requirements

	Area	Baseline
IR Vis.	1,024 m² 9,216 m²	6,000 km 303 kill
1R Vis.	64 m² 576 m²	2,400 km 1?0 km

The Space Infrared interferometer

Roger Angel
University of Arizona

Direct Detection From Space
What Are We Looking For?

- ❖ Find **out if nearby stars have habitable planets**
- ❖ Use IR photometry to find size and **temperature**
- ❖ Get orbits by direct imaging (relatively fast)
- ❖ **Search planet spectra in** $10\,\mu m$ **band for**
  - water $7\,\mu m$ ·› habitability
  - ozone $9.5\,\mu m$ ·› photosynthesis
  - CO_2 $15\,\mu m$ ·› atmosphere
  - Other features (IR and optical) are much weaker
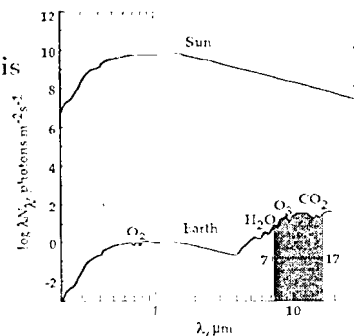
Planetary Atmospheric Spectra
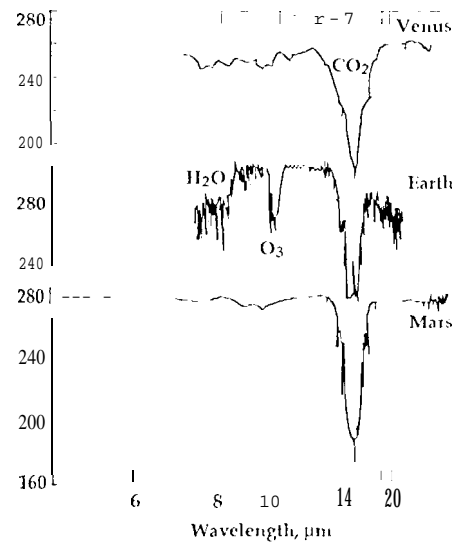
Ozone Traces Oxygen
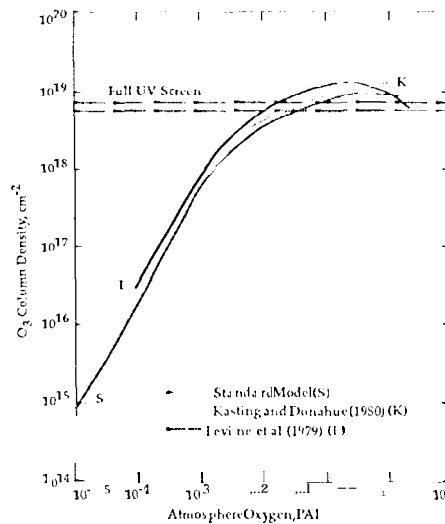
Prehistoric Oxygen Concentration on Earth
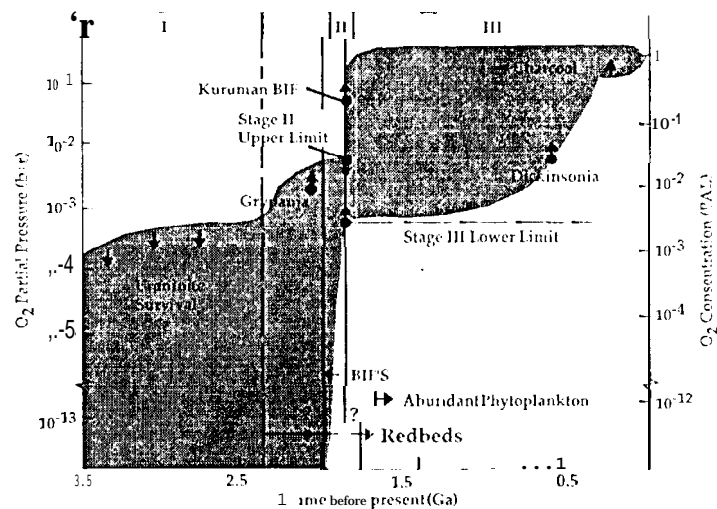
Our Solar System **Seen** From **A** Distance
Model at 10μm **from** 10pc
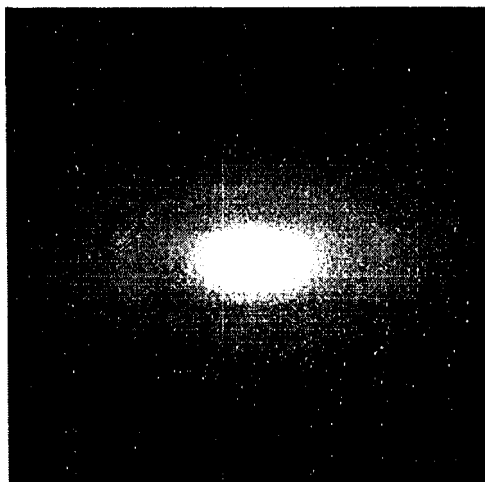
A Search For Planets **Must Allow For:**

◆ Possibility of multiple planets
- Several planets of similar 10 μm brightness, as in solar system.

◆ Diffuse dust emission
- Integrated zodiacal emission in solar system is 300 x brighter than Earth, mostly within 1 AU.

◆ But expect the **unexpected**
- Any detectable planet will be interesting (e. g., self luminous gas giants like Jupiter around the most populous M stars)
- Telluric planets with strong CH_4 (7.6 μm) or NH_3 (10.5 μm)

Survey Nearest 1000 **Stars For Planets**

◆ **Best candidates for habitability**
- **Star** type
    - similar to sun F3-K2
    - 4x brighter to 4x fainter
- Orbital distances
    - Match solar constant
    - 0.5 AU 2 AU
- 72 optimum candidates
    - 8 F stars
    - 44 G stars
    - 20 early K stars

◆ >200 stars are good **general candidates**

Instrument **Performance** Targets

◇ Sensitivity to analyze flux from an Earth out to 13 pc
◆ Resolution to isolate habitable planet light from the
  star at maximum distance of 13 pc
  - F2 star   2 AU = 0.154 arcsec
  - G2 star   1AU = 0.077 arcsec
  - K2 star 0.5 AU = 0.038 arcsec
◇ Spectral bandwidth - 7 to 17 μm needed to detect
  strongest molecular features
  - CO_2 **absorption** is 2.5 μm wide (FWHM) and **40%** deep
  - Ozone feature is 0.5 μm wide and .- 25% deep
  - Water is 2 μm wide, low photon flux
  - Note: methane requires ×100 better sensitivity/ruolution
◇ Spectral **resolution**
  - $\lambda/\Delta\lambda = 20$
  - Signal-to-noise 20 needed for 5σ detection of ozone **and** water

---

Instrument Size **Set by** Diffraction

◇ Diffraction **at wavelength** λ and **required angular
  resolution** α **together set scale** size **S**

  $$s \propto \lambda/\alpha$$
  $$S \propto \lambda/0.03S \text{ arcsec}$$
  $$S \propto 40\text{-}90 \text{ m for } \lambda \text{ -7-17 pm}$$

◆ The actual size **might** be greater than 40-90 m, to get
  very strong contrast to suppress star

  > **Scale** size is too large **for** filled aperture.
  > Interferometer is recommended

Collecting Area Set by Photon Noise

◇ IR photon flux from planet is not ridiculously small
- HST routinely measures smaller photon rates in the visible

◇ Problem is photon **noise** in background

Representative Photon Fluxes λN_λ
(Octave bandwidth at 10 μm)

	Photons/m²/sec
◇ Solar system twin at 13 pc	
• Earth twin	2.25
• Exo-zodiacal emission	600
• Sun twin	8,000,000
◇ Background fluxes	
• Telescope (T~35K)	<100
• Local zodiacal emission	60,000
• Imperfect star rejection	

Steps to Minimize Nonsignal **Photons**

◇ Eliminate atmospheric and telescope emission
- Must be in space with mirrors at ~35K

◇ Suppress the star relative to the planets by 10^5-10^7
- Interferometric or coronagraphic techniques essential

◇ Overcome diffuse sky background
- Local zodiacal dust causes bright sky emission at 10μm
- For 1-m aperture, local background is 10,000 times brighter than a planet at 10 pc
- Possibilities for reduction
  - Large single aperture, whose sharp diffraction limited planet images will stand out against the bright sky. Requires a very large diameter (> 50 m)
  - Interferometer with large elements (~6 m)
  - Go out to 5 AU from the sun, (the distance of Jupiter) where the sky is dark – can then use 1.5-m elements

Steps to Minimize Nonsignal Photons
(Cent'd)

⬧ Objective is to suppress the three controllable sources of background emissions below the level of the exo-zodiacal emission

⬧ If this objective is met, a collecting area of ~71112 can overcome photon noise from the exo-zodiacal emission from a twin of our solar system at 13 pc

Summary – Practical Design Requirements

⬧ Use interferometer

⬧ ~70 m interferometer baseline to resolve planet/star

⬧ Operate at 5 AU from sun for dark $10\mu m$ sky

⬧ Cold 1.5-m mirror elements give adequate signal

> At photon noise of exozodiacal cloud
> • ~1/2 day integration will give image
> • ~45 days integration for spectra

⬧ interferometer requirements

　• Need to suppress stellar emission

　• Need to avoid systematic error from non-circular zodiacal clouds

　• Need to distinguish multiple planets

Evolution of Interferometer Designs
Bracewell Two-Element Nulling interferometer

◇ Mirrors **superpose achromatic** wavefronts with π **phase differences**

◇ Summed amplitude **is zero across pupil**

 • Airy pattern vanishes for point star on axis,

 • Signs] from off-axis planet is {transmitted (A phase $\neq \pi$)
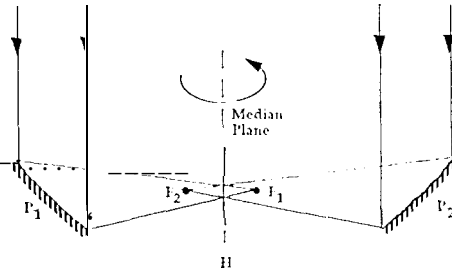
◇ Fringes **are on the sky** and not in focal plane

◇ Spins about **axis to star**

 • Star **remains** in central null

 • Planet signal is modulated as a function of 2θ (twice the rotation angle)

* Bracewell, 1978.

Evolution of Interferometer Designs
Nulling Interferometer

◇ **Problems with two-element nulling interferometer**

 1. Finite stellar disk is not fully suppressed

  - Null fringes too shallow and widely - spaced

 2. Exo-zodiacal emission is not suppressed

  Elliptical cloud gives 2θ signal as fringes rotate (same as a planet)
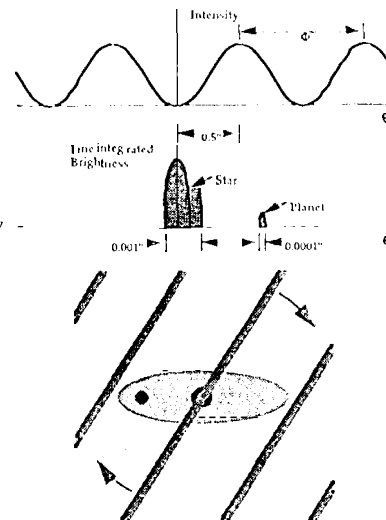
OASES Concept
(Univ. of Arizona)

⬥ Nulling interferometer with **4** elements in-line

⬥ Linear fringes on the **sky — all planets pass** through maxima

⬥ Central null **is** wide **and very** deep

⬥ Rotates like Bracewell **interferometer**
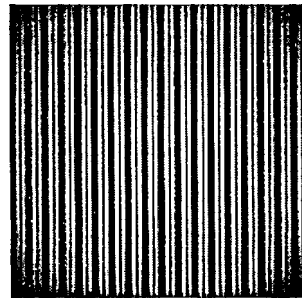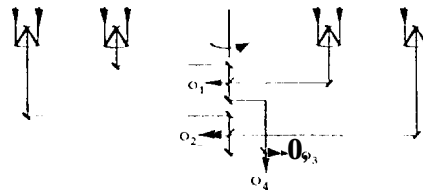
Key Features of OASES Concept

⬥ Interference **null** much **broader** and deeper

⬥ Sizes chosen to place first maxima at **0.037** arcsec

- Bracewell (a)   28 m
- 4-element OASES (b)   75 m
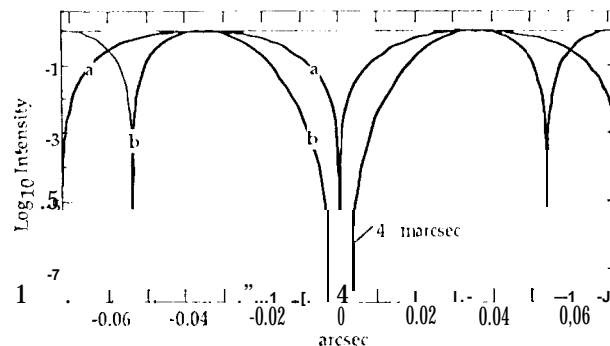
How the Linear Interferometer Makes a Very Deep Null

♦ Think of **ii as a** long and a short Bracewell interferometer **superposed** and **with opposite phases. At the common central dark** fringe, the **amplitudes both pass through zero,** but **with** equal and **opposite gradients. The** summed **gradient is then also zero**

Bracewell

Oases

Bracewell $I \propto \theta^2$

Oases $I \propto \theta^6$

add sin 2θ

0   s   Pointing Angle   0   5
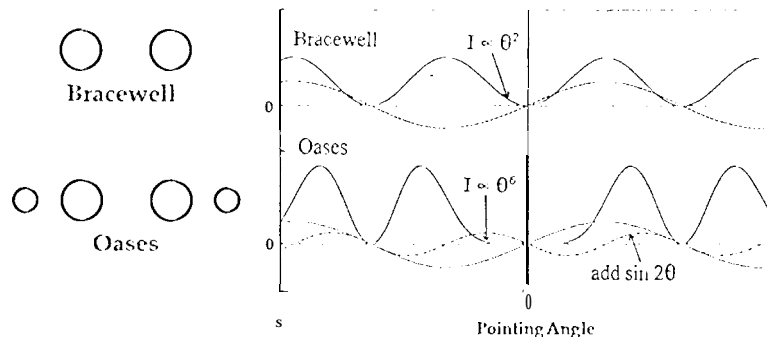
Other **Requirements for** Deep **Null**
Maintain Starlight Null at ~10⁻⁶

♦ Can such **mathematically** perfect **cancel] at ion of the star** be realized in practice?

Example of wavefront folding (corner cube) interferometer

• The null must be achromatic
   Path delay won't work
   One solution is polarization rotation
• Interfering wavefront phases
   must match to λ/6000 (-1.5 nm)
• Interfering wave front
   amplitudes must match ~10⁻³
• **Amplitude and** especially phase control arc made possible with the use of a single mode spatial filter such as a single mode fiber
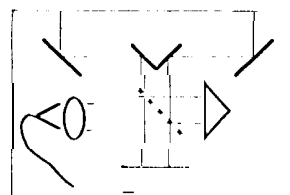
Inside a single-mode fiber there is only amplitude and phase. The shape of the wavefront (from imperfect optics) is lost.

♦ Pathlength can be controlled to nm precision using laser metrology as in ground-based interferometry

Shao and Colavita, 1992

Taking Advantage of Deep Null

◆ Long baseline can be used with no star disk "leak"
  • Sharp, fine fringes
  • Complex modulations from planets
◆ Allows distinction from diffuse zodiacal cloud
  • Cloud gives smooth, low-frequency modulation

ExNPS Infrared Interferometer
Illustrative Concept

◆ Builds on **the OASES concept**
  • 4-element linear interferometer
  • 1.5-m apertures
  • 75-m baseline
◆ **Science capability**
  • **image planetary** systems
    1013 pc
  * **Spectroscopic** study of planets
    in selected systems
◆ Challenges
  • Potential for other astronomical observations
  ○ Improve suppression of em-zodiacal emission and local
    zodiacal photon noise

ExNPS

The Space Infrared Interferometer. D-11
10/20/95
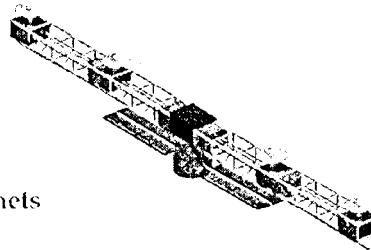
ExNPS Infrared interferometer Illustrative Concept
Image Reconstruction of Hypothetical Planets

◆ Signals recorded at 10 μm with Space Infrared
Interferometer for 1(1 hours

- Modulation patterns
  depend cm radius and λ
- (e) is sum of planets a
  through d, all four same
  brightness as Earth
- (f) shows (e) + photon
  noise, calculated for
  exo-zodiacal cloud of
  same character as
  solar system's

Example planetary system

Rotation angle
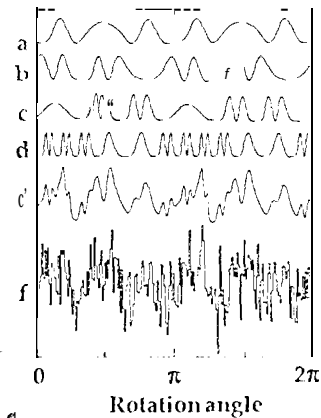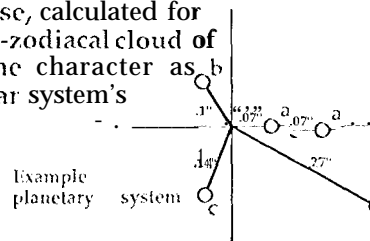
ExNPS Infrared Interferometer Illustrative Concept
Image Deconvolution

◆ Data set – intensity vs rotation for 10 bands, 7–17 μm
plus random noise

◆ Method -- cross correlate the data D with the signals
T for a source at each image pixel. 20 modulation
fitted and removed from simulated data to minimize
zodiacal cloud signal

- Integral over wavelength is
  equivalent to adding different
  baselines – polychromatic image
  has full UV Plane cover

$$i(\alpha, \beta) = \sum_{\lambda} \sum_{\omega} D(\lambda, \omega) T(\alpha, \beta, \lambda, \omega)$$
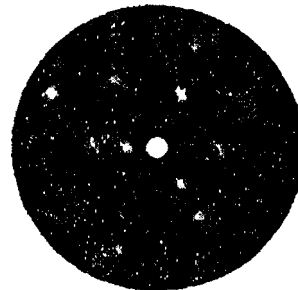
Angel and Woolf, 1995

ExNPS **infrared interferometer illustrative Concept**
Noise **and** Sensitivity of Deconvolved **image**

◆ 10-hour **integration**

- 4 X 1.5-m elements
- Model system at 14 pc, resolution 0.01 5"
- image doubling from symmetry, removable by slight offset and longer integrations
- Inner radius limit is 0.06 arcsec for 75-m *baseline*
- G2 habitable zone **(1 AU)** resolvable to **15** pc
- K2 habitable zone **(0.5 All)** resolvable to 7.5 **pc**

ExNPS Infrared Interferometer Illustrative Concept
Spectroscopic Performance

◆ **SiSnal-to-noise** set by **aperture** and zodiacal cloud **strength for** Earth **twin at 13** pc

- CO_2 detection (5σ) ~1 week
- O_3 and H_2O detection (5σ) ~6 weeks

◆ **Assumes**

- 20% overall quantum efficiency
- 4 Exo-zodiacal cloud is like solar system
- Sensitivity limited by noise from exo-zodiacal cloud
- 4 x 1.5-m elements
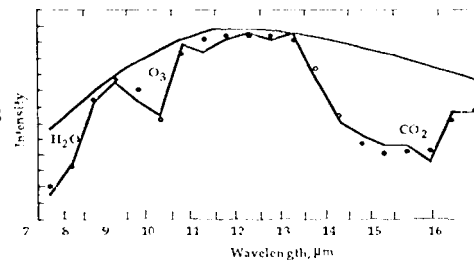
ExNPS Infrared Interferometer Illustrative Concept
Example of 4-year Observing Plan

- ◇ 1 year: complete imaging survey of 50% of sky
  - ◦ Identify 50 optimum habitable zone candidates
  - ◦ Identify 100 other single stars
- ◇ 3 years: follow up with spectral observations
  - ◦ Observe 50 stars for CO_2 1 week each
  - ◦ Observe 12 stars for H_2O and O_3 6 weeks each

Evolution of Nulling Interferometer Concept
Darwin Concept (Proposed to ESA)

- ◇ 4-aperture linear interferometer provides viable solution, but alternate concepts are being explored
  - ◦ Uses 2-dimensional circular array with multiple aperture to obtain deep interference null
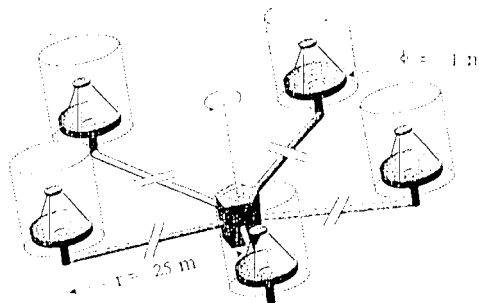
Schematic of Darwin 5-element concept

Leger et al., 1995

Evolution of Nulling Interferometer Concept
Darwin Concept

♦ **Odd symmetry allows sharp distinction in rotation signals**
  • Planet 5θ
  • Zodiacal cloud 10θ

♦ **Problems with 5-element solution**
  • For some radii and wavelengths, planets don't give a strong interference peak at any rotation
    - Multiple configurations of interferometer elements is needed to obtain full spectral coverage
  • Data does not yield a picture, possible confusion of multiple planets

Star positioned on center
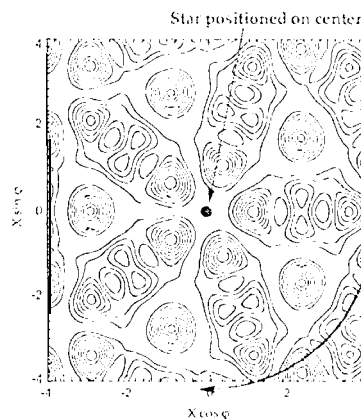
Evolution of Nulling Interferometer Concept
Phase-Shifting Nulling Interferometer Concept (JPL)

♦ **Many exo-zodiacal disks could be much brighter/ denser than our solar system zodiacal disk**

♦ **A general solution is higher angular resolution**
  • Planet flux in 1 pixel of the synthesized image > than the exo-zodiacal flux
  • Resolution imaging must remain with 10^{-6} nulling of starlight

♦ **Each 3-element array produces a 10^{-6} null**
  • Planet light from two of these arrays is interfered in phase and in phase quadrature
  • Resolves 2θ component of exo-zodiacal emission and 180° ambiguity in planetary position

Synthesized image
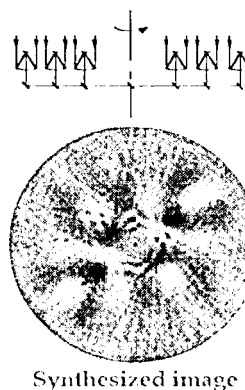
Unanswered Scientific Questions

⬧ **Are planets common around stars?** The further we **have to look, the** bigger the **instrument we will** need

⬧ Brightness **of 10** μm **zodiacal cloud of candidate stars**
  - If -solar, 4 element interferometer may suffice
  - If several times solar, more elements and/or different configurations **should** be considered
  - **If baselines** become **excessive, separated** spacecraft **architecture** could be considered
  - If cloud -100 times brighter, only interferometers with very-large filled aperture can suppress photon noise

⬧ Distance **from** sun **to** get 300-fold reduction in local zodiacal background - 3 AU? or **5** AU?

Key Technology Needs

⬧ ExNPS Interferometer **requires variety** of advanced **technologies**
  - Large deployable/erectable structures
  - Lightweight spacecraft with solar-electric propulsion for 3-5 AU operation
  - Actively controlled, stable structures
  - Interferometric metrology and beam combination
  - Interferometric nulling
  - Passive cooling to 35 K
  - Very low- noise infrared detectors

⬧ Agressive technology development program required
  - <'combination of ground and space testbeds

Conclusions

- If **solar** system **is typical, we know how** to build a **system to search** to 13 pc **(nearest 1000 stars)**
- Investigated **how** to image **extra solar planets**
  - One configuration has been studied thus far
  - Other interferometer configurations should be studied
- Approach is believed to be resilient to anticipated variety of solar systems and exo-zodiacal clouds
- **As more is learned about the** nature **of** exo-zodiacal **disks,** the **interferometer concept** should **be refined**
- **No show stoppers** anticipated
- No major **technology breakthroughs** required
- In next **5 years**
  - Develop optimum designs and technology for different levels of sensivity
  - Find out how typical we are

Technology Challenges

Domenick Tenerelli
Lockheed-Martin

Space IR-Interferometer Technology

◆ ExNPS is "technology rich"
- **Advances** state-of-the-art across a broad front of space technologies
- Within our near term reach (5-10 years)

◆ Will capitalize on existing programs, such as
- Space Infrared Telescope Facility (SI RTF) for low **temperature** technology
- Astrometric Interferometer Mission **(AI M)** for interferometer technology
- New Millennium for spacecraft technology
- NASA Solar-electric Technology Application Readiness (NSTAR) for propulsion technology

◆ In addition, dedicated technology developments and flight experiments will be needed

Core Technologies

ExNPS Interferometer

- Cryogenic Optics
- Beam Control and Nulling
- Advanced Propulsion
- Vibration Isolation and Structural Quieting
- Science Focal Plane
- Metering Structure
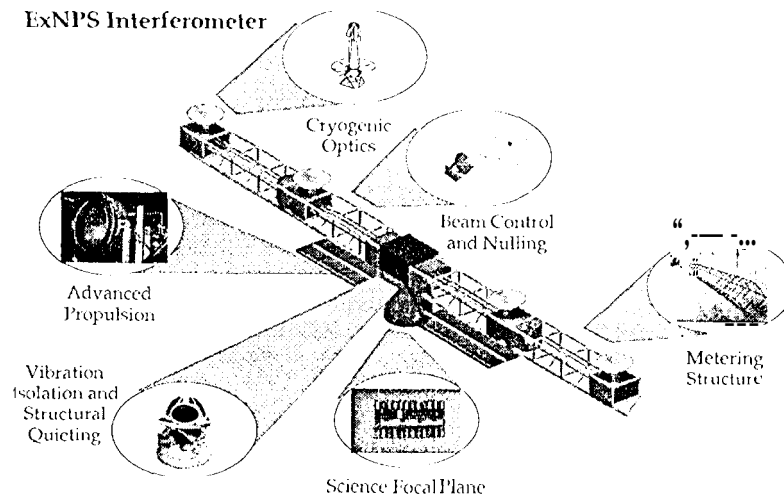
Active Optics Achieves Needed Precision
Underlying Metering Structure Need Not be Precise

Positional Precision

Physical Dimension (Length of Structure)

- 100 m
- 10 m
- 1 m
- 0.1 m

Metering Structure — 1 Hz
Optical Delay Line - Coarse Stage — **10 Hz**
Optical Delay Line - Fine Stage — 100 Hz

μm   mm   cm

Precision

Palomar testbed optical delay line

Physical Dimension (Length of Structure)

- 1 m
- 0.1 m
- 0.01 m

Collecting Aperture — 0.1 Hz
Steering Mirror - Coarse Stage — 10 Hz
Steering Mirror - Fine Stage — 100 Hz

μasec   masec   asec

Precision

Steering mirror used on Hubble Space Telescope

Conventional approach used on ground and space interferometers

---

Metering Structure

- Deployable option (already flown in space)
    - 30 m Space Station segment deployment accuracy of ~1mm
- inflatable option (offers better packaging efficiency)
    - 30 m strut deployment accuracy of - 10 cm
    - Needs "rigidizable" materials technology development
- "Some assembly required" option
    - Astronauts have assembled 14-m truss structures to -1 mm accuracy on STS-61B
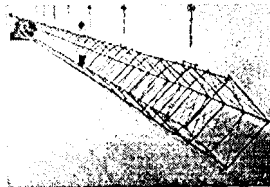
Deployable (i ASI Mast).
Ilown onSpace Shuttle STS-46
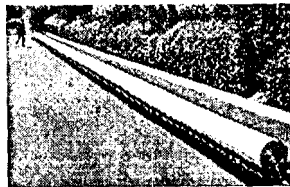
Inflatable. To be flown on
INSTEP experiment
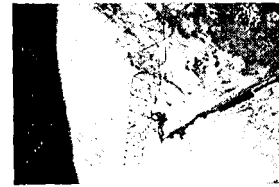
Astronaut holding assembled
truss at end of Shuttle arm

Vibration Isolation and Structural Quieting
Decouple Spacecraft Disturbances from Optical Train

- Reaction wheel and solar array disturbances from spacecraft can be isolated from optical train
- Key technologies have been demonstrated at room temperature
    - Multi-axis vibration isolation
    - Active and passive structural damping
- Demonstration at 35K needed

Modeling accuracy achieved
for Micro Precision
Interferometer testbed

Six axis isolation stage

Typical active vibration
isolation performance

Beam Control and Nulling

♦ **laboratory breadboard has demonstrated** nulling at 10^{-3}
  - Nulling al 10^{-6} could be demonstrated in 2 years
♦ Required picometer laser metrology is currently available
  - Requirement is 10-30 picometers
  - State of the art is <1 picometer
  - Requires flight qualification
♦ Spatial **mode** filter **for** 10-µm band
  - Mater al selection and manufacture required (no show stoppers)

existing laser metrology performance
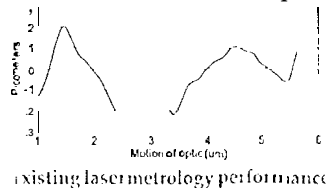
Cryogenic Optics

♦ **Cryogenic (-351<) telescopes**
  - State of the **art is 0.85** m, diff raction limited at 6µm (SIRTF)
  - Requirement **is 1.5 m,** diff raction limited **at 2** µm
  - **Beryllium** and **Silicon** Carbide offer **attractive options**

0.85 m Beryllium mirror (Infrared   0.63 m reaction bonded Silicon Carbide mirror
  Telescope Technology Testbed)   (back **surface** shown)
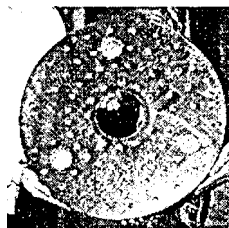
> Reasonable extension of SIRTI
> technology for Beryllium and Silicon
> Carbide within 5 years.

Science Focal Plane

- 7-17 mm detector noise requirements
  - <2 e⁻/sec dark, <8 e⁻ read noise
- Detector options
  - Solid state photo-multiplier (SSPM)
    - Offers zero read noise (photon counting)
  - Extension of SIRTF Si:As arrays
    - Noise 10x too high
  - Quantum Well Infrared Photodetector (QWIP)
    - Can operate > 10K, noise 100x too high
- Cryo-cooling options
  - Sorption cooler (I OK demo soon)
    - No vibration or store'ci cryogen
  - Stored cryogen (USC SIRT F technology)
  - Mechanical coolers (available > 10K)
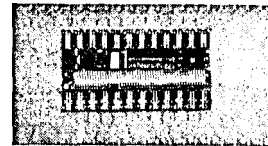
Solid state photo-multiplier test arrays
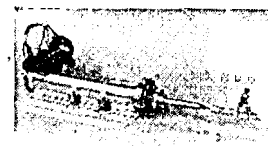
10K sorption cooler (compressor shown)

Technology investment is required to improve dark count by 10x in 5 years

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Advanced Solar Electric Propulsion (SE]')

- Enables new family of Earth-Venus-Venus gravity assist trajectories
- NSTAR is demonstrating capability
  - 0.1 N thrust engine
  - 3360 sec specific impulse
  - Requires 8 kW power
    - Available in needed portion of new trajectory

NSTAR 30 cm Xe engine
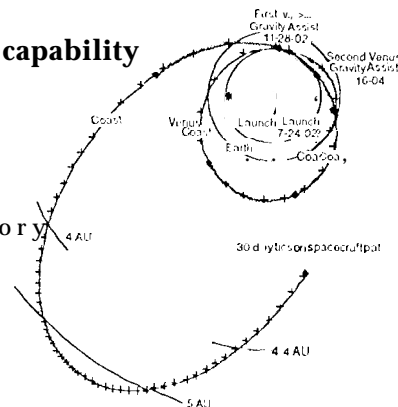
Earth-Venus-Venus gravity assist trajectory delivers 170(1 kg to 5 AU in 4 years using Atlas IIA launch vehicle. ΔV = 4.3 km/s

Advanced Spacecraft Components

◇ Needed spacecraft technologies are either available, or are being developed for commercial satellites or New Millennium

- Powerful lightweight computers
- Lightweight x-band transponders
- High output deep space solar arrays
- Ultralight structural materials
- Advanced lithium batteries
- Solid state data recorders
- Autonomous star trackers
- Solid state gyros
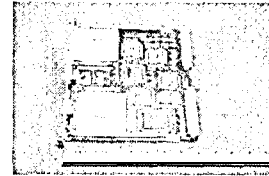
R-6000 computer
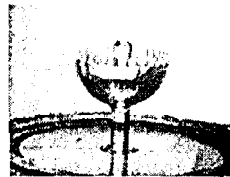
Solid state gyros
(hemispherical resonator shown)

Autonomous star tracker

Comparison to HST-era Capability

◇ Power required compared to HST

Power (W)

1200
1000
800
600
400
200

OTA SIC & DH   S/C   DMS   EPS   COMM
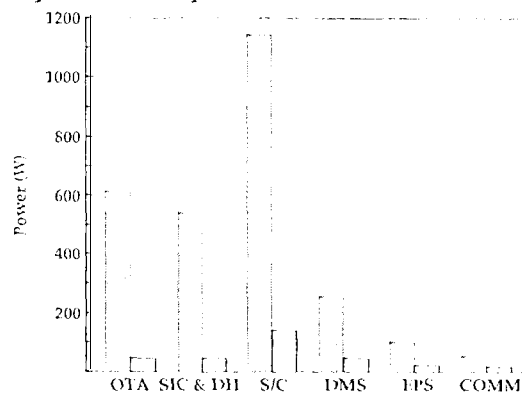
Technology improvements over past 10 years
dramatically reduces power requirements

*Spacecraft attitude/control numbers included in spacecraft power need further refinement.

Technology Summary

Component	ExNPS Requirement	Current State-of-the-Art
Cryogenic optics	• 1.5 meter aperture, diffraction limited at 2 µm, operational temperature of 35K	• 0.85 meter aperture, diffraction limited at 6 µm, operational temperature of 5K (SIRTF specifications)
Achromatic nulling	• 10^6	• 10^3
Laser metrology	• 50 picometer precision	• <1 picometer precision
Metering structure	• Total span of 70 meters in 20 meter segments, dimensionally stable at 35K	• 30 meter FAST Mast deployable, flown on Shuttle, being qualified for Station • 30 meter inflatable, not space rigidizable • In space assembly by astronauts, STS-61
Focal plane detector	• 7-17 µm wavelength <2 e-/sec dark noise < 8 e- read noise	• Si:As BIB (SIRTF), 5-20 µm wavelength <10 e-/sec dark noise <55 e- read noise
Passive Cooling	• 35K at 5 AU	• 50K at 1 AU (SIRTF)
Cryocooling	• 5-10K (depending on detector type)	• 10K sorption or mechanical coolers
Cryogenic mechanisms	• Fast steering mirrors, optical delay lines must operate at 35K	• Current designs operate at room temperature

Solar electric propulsion	• existence of SEP enhances mission, can use what is being developed by NSTAR	• 0.1 N thrust
		  3360 sec specific impulse
		  8 kW power

Implementation Approach
"Single-Minded" Option

⬥ **Dedicated precursor mission (exo-zodiacal mapper)**

  • 20-meter baseline "scale model" of Space IR Interferometer

  • Would provide detailed 10 µm mapping of exo-zodiacal disks of target stars

  • Would demonstrate all technology components in a cold environment (L2)

Implementation Approach
"Integrated" Option

◇ Utilize existing missions as much as possible to demonstrate technology

- SIRTF (Space infrared Telescope Facility)
  - Cryogenic telescope (5K)
  - Passive cooling (501< at 1 AU)
- Enhanced AIM (Astrometric Interferometer Mission)
  - Demonstration of key technologies (at ambient temperature)
    - Deployable structure (--20 meters)
    - Fast steering mirror and optical delay line mechanisms
    - Optical nulling
  - Integration of technologies into a working space interferometer
- New Millennium
  - Low mass spacecraft technologies
- NSTAR (NASA Solar Electric Technology Application Readiness)
  - 0.1 N thrust Xe ion engine

Implementation Approach
"Integrated" Option (cont'd)

◆ **Augment as needed with dedicated ground and space experiments**

- **Ground-based** demonstration
  - Cryogenic mechanisms
  - Focal plane detectors and cryocooler
  - System integration and operation (using testbeds and thermal-vacuum chambers)
- Space-based demonstration
  - Deployment and microdynamics of metering structure (use laser metrology for measurement) in cold environment

Key Trade Issues

* Detector operating temperature vs. cryocooler performance can have a large impact on the mission design and the need for stored cryogen
* A trade exists between deployable or space erectable metering structures, If astronauts are used, then a low thrust propulsion system is required to lift the interferometer from 1 ow earth orbit
* A trade exists between sky coverage, mission duration, and the eccentricity of the orbit. A Jupiter flyby may enhance sky coverage by raising perihelion of the orbit
* Strength of exo-zodiacal drives baseline length and system architecture. Required resolution could require separated spacecraft

Assessment

* All key technologies required could be in hand in 5 to 10 years with continued vigorous technology investment
  * Infrared detector technology must be aggressively supported
* NASA should continue to invest in breakthrough technologies that could radically enhance the mission or significantly reduce the cost
  * Large filled aperture optics (-50 m diameter)
  * High-thrust solar electric propulsion to enable flight from low earth orbit

Ground-Based Element

David Tytler
University of California, San Diego

Goals and Objectives

◆ Science goal: near-term discovery **of** planetary **systems**

- **Are** planets common throughout the galaxy?
  - Which are **most** common: Jupiters, Uranus', Earths
  - What are the sizes and shapes of [heir orbits?

  What types of stars **have** planets?

◆ Survey the exo-zodiacal intensity around nearby stars (in conjunction with SIRTF)

- Impacts design of Space IR 1 nterferometer

◆ Advance interferometric techniques with new technologies and observations

◆ Provide a continuous stream of discoveries

- Starting now!

Understanding Planetary Systems

◆ There have been major advances in most areas since the TOPS report (1992) and breakthroughs in three areas
  • Narrow angle astrometry will find Uranus-mass planets
  • Microlensing will test if Earth-mass planets exist
  • Advanced adaptive optics will directly detect Jupiter-sized planets from the ground

◆ Some of what TOPS saw as first-phase space **programs** can now be done from the ground

> 0.5 Jupiter-mass planet found orbiting
> 51 Peg (G star) October 1995

Typical Mass Sensitivity

Radial Velocities
Astrometry:
 One 10-m Telescope
Palomar Testbed Interferometer
New Interferometer
Microlensing
AO/Balloon/HST[a]
Space IR Interferometer[a]

1   10   100   1000
Venus Uranus Neptune Jupiter
Earth Saturn
Planet Mass (Earth Mass Units)
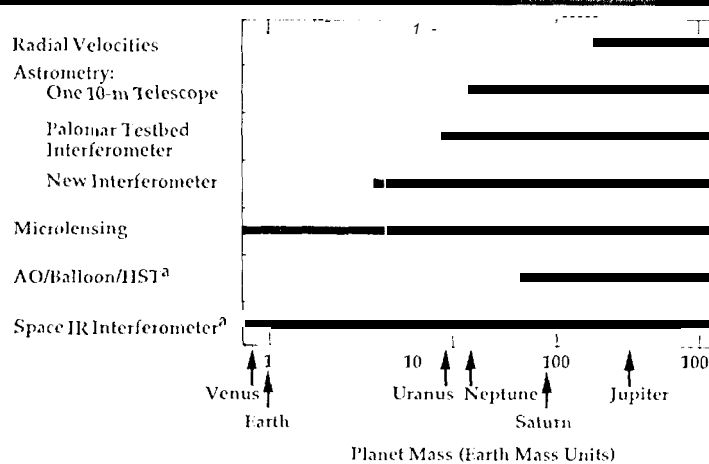
[a] The direct imaging methods are sensitive to planet size, albedo and temperature, rather than mass

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Typical Orbital Sensitivity

Radial Velocities

Astrometry:
  One 10-m Telescope

  Palomar Testbed
  Interferometer

  New Interferometer

Microlensing

AO/Balloon/HST

Space   IR   Interferometer

↑ Venus ↑ 1   ↑ Jupiter ↑ Saturn ↑ 10 ↑ Neptune
        Earth   Uranus

OrbitalRadius **(AU)**
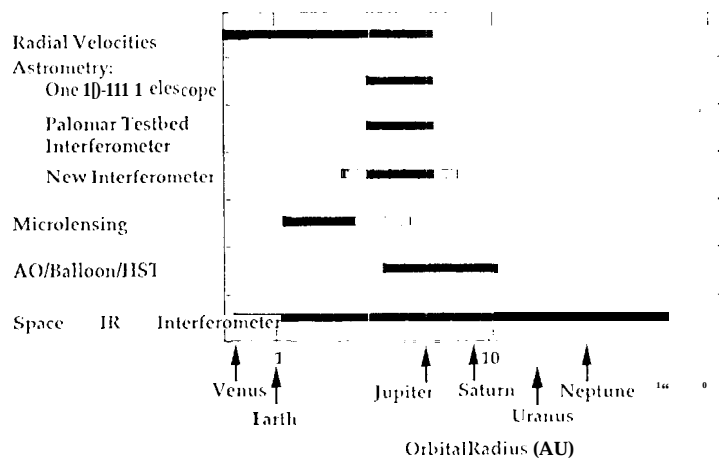
L ⅃ Reduced Sensitivity

Number of Stars Searched

4

Radial Velocities   1000

Astrometry:
  One 10-m Telescope   ■ 40

  Palomar Testbed
  Interferometer   ■ 60

  New Interferometer   500

Microlensing[a]   3500 →

AO   3 0

Balloon   7 0

Hs'I   — 10LI

Space IR Interferometer[b]   250

  0   100   500   1000
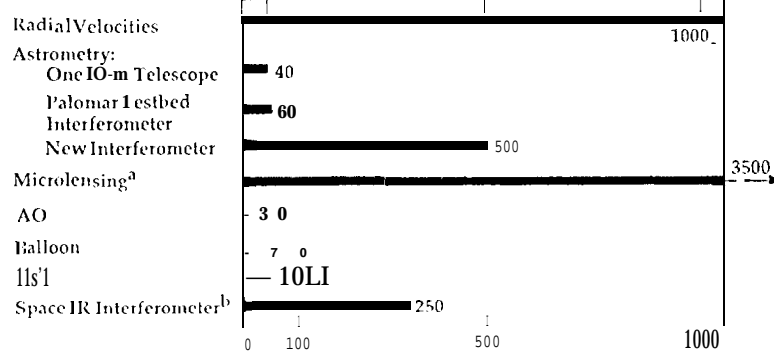
· 1 Efficiency depends on planet ma - 1% for earthmass, 18% for Jupiter mass
   Microlensing alone uses distant stars.

h Includes spectroscopy of detected planets

Planet Information

Radial Velocities
Astrometry:
    One 10-m Telescope
    Palomar Testbed
    Interferometer
    New Interferometer
Microlensing
AO/Balloon/HST
Space IR Interferometer

Common ? Jupiters
Uranus?
Earths?
Which nearby stars have Jupiters ?
Uranus?
Earths?
Orbits (size, shape) colors for Js
How many large planets ?
Are there planets in habitable zone ?
Size ?
Atmosphere ?
Water ?
Life ?

[   ] Partial answers   Note. All indirect methods, especially astrometry give
information on planet mass

Ground Based Astrometry

◇ Differential astrometry is the most sensitive indirect method for nearby stars

  ● Major advances have increased astrometric sensitivity 100×

    - Saturn-mass planets detectable with low-cost upgrades to existing facilities

    - 10× Earth-mass planets detectable with new facilities

  ● Ground-based astrometry will advance interferometer technology

◇ Accuracy improves with good seeing, large apertures, long baselines, and bright reference stars near bright targets

◇ Physical limit set by star spot noise (1 µas)

  ● Need 0.5 µas for detection of Earth-mass planets

Accuracy of Narrow-Angle Astrometry
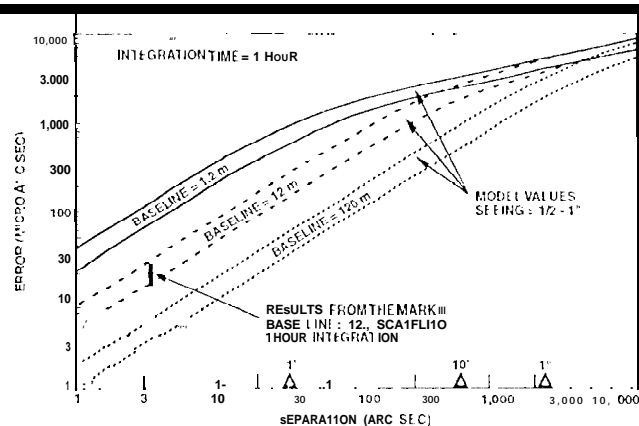
Differential accuracy proportional to $\dfrac{1}{\text{aperture}}$ or $\dfrac{1}{\text{separation}}$

From Shao and Colavita, 1993

Single Aperture Astrometry

- ◇ Current accuracy with a 0.76-m **telescope is** 3000 μas per night
- ◇ Advantages of a large telescope
  - • Atmospheric noise between target and reference drops
  - • More reference stars with sufficient photon flux within each field
  - • More reference stars are nearer the target star
  - • Demonstrated 200 μas at Palomar 5m
- ◇ Keck telescope (90 μas accuracy) could **measure** 50 nearby stars (50% **M stars)** to detect **Uranus-mass** planets **in** 5-year orbits

Interferometric Astrometry
Palomar Testbed Interferometer (PTI)

- PTI is a NASA instrument intended to demonstrate differential, narrow-angle astrometry
- Dual interferometers observe target and reference stars simultaneously
- Fringes are tracked with moving delay lines
- Laser metrology controls systematic errors over the 100-m baseline

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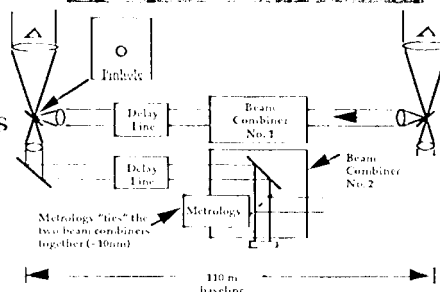
Palomar Testbed Interferometer
Science Potential

- Facility ready to begin science in early 1996
- Preliminary results suggest design goal will be exceeded (50 μas/hour at 20 arcsec separation)
- A possible science program:
  - Science community participation through NASA AO/NRA process
  - Search 60 stars (F, G, K) for Saturn mass planets to 5-AU
  - Search a few stars for Uranus-mass planets
  - Survey a few wide binary stars which give 10 times improved accuracy when both are bright
- Adding a third telescope for East-West baseline is required for astrometry
- Adding two beam combiners will provide interferometric imaging

Palomar Testbed Interferometer: First Fringes
(α Cygni - 24 July 1995)
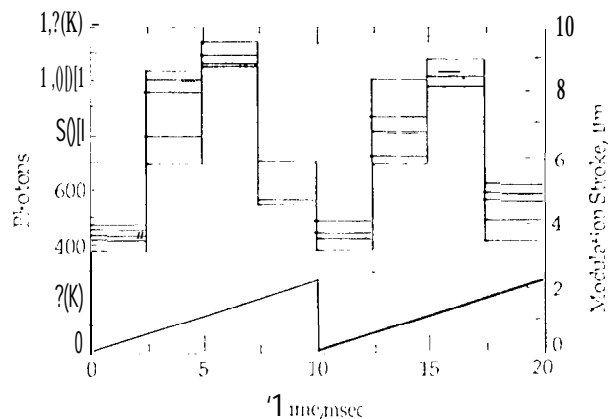
The vertical scale shows photons per 2.5 msec time-bin vs time. The modulation of the photon flux is due to a path length modulation of 1 wave p-p in 10 msec from a piezoelectric driven mirror

New Astrometric Interferometer

◇ An interferometer, with four 2-m **telescopes on orthogonal** 100-m **baselines,** will improve accuracy
- 20 μas/hr if atmospheric turbulence extrapolates to 100-m
- 5 μas/hr if turbulence weakens, as suggested by both Keck and early PTI measurements

◇ Larger apertures → 90% of targets have a reference stars (only 1 O% for PTI 0.4-m apertures)

◇ **A** possible **science** program:
- Search 500 stars (5–30 μas) for Uranus-mass planets at >5 AU
  - 60% M stars; 40% F, G, K stars
  - 1 hour integration, 4 times/year
  - Telescope time sets limit of 500 stars
- Detect some planets on 12-year orbits in <6 years
- Replaces both single aperture and PTI astrometry

Comparison of Astrometric Surveys

Assumptions:
- Solar Mass Star @ 10pc
- Multiyear Observing Programs
- Dedicated Instruments
- Earth-mass planet @ 1AU
- Uranus-mass planet @ 5 AU

Labels in figure: AIM; New Astrometric Interferometer (Ground-based); Star Spot Noise; Palomar Testbed Interferometer; Single Telescopes

Y-axis: Number of Stars in Program (10, 100, 1,000)

X-axis: Astrometric Accuracy, µas (0.1, 1, 10, 100, 1,000) — Earth, Uranus

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Radial Velocities

- ◆ Goal: **Survey 1000** nearby stars for Jupiter-mass planets
  - ⁰ Extend early astrometry to 10X number of stars
  - ● Check astrometric detection of Jupiter-mass planets
- ◆ Fastest for bright (F,G) stars, slower on **faint** (M) stars and **independent of** distance
- ◆ Current **surveys:** 5-10 **m/s on** 30 stars; no Jupiter-mass planets **detected** in **7 years**
- ◆ Sensitivity
  - ● Long term accuracy demonstrated (<4 m/s)
  - ● Short term precision demonstrated (~3m/s)
  - * Stellar noise limit not yet detected (may be 1-3 m/s)
- ◆ **A possible** science program
  - ● 35 nights/yr on Keck (enhanced HIRES); 190 M and K stars
  - ● 100% of 2m telescope for **800** nearest (bright) F, G, K stars
  - ● "Technology development to achieve <1 m/s accuracy

Radial Velocity Detection of A Planet

◆ Mayor and Queloz (Geneva Observatory) found *radial velocity* signature of planet around 51 Peg, a nearby G star (~13 pc away)

◇ Result confirmed by Marcy and Butler (Lick observatory)

◆ Inferred properties of planet
  ◦ -0.5 Jupiter mass
  ◦ 4.2 day orbital period
  ◦ ~0.05 AU orbit (inside Mercury's orbit!)
  ◦ Distance from star implies 1300 K surface temperature

◇ Direct detection of **this** hot planet may be **possible** with Palomar Testbed Interferometer at 2µm

Detection Of a Planet Orbiting 51 Peg
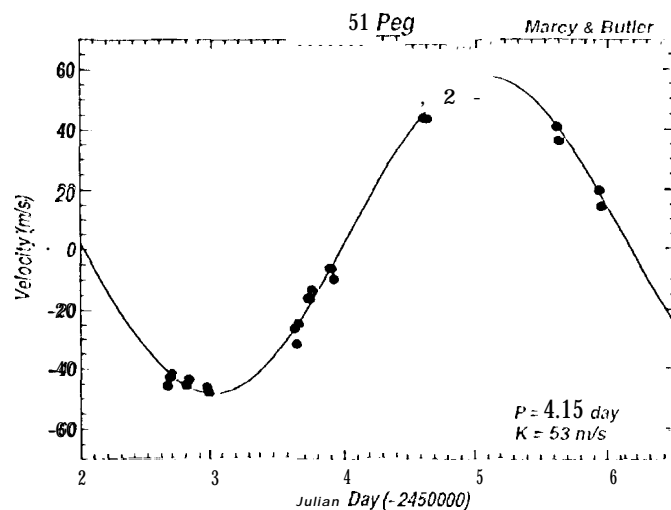
Microlensing

◇ Goal: Determine frequency of planets down to Earth mass

◇ Gravitational microlensing is well-established consequence of general relativity

◇ Current observations from MACHO* collaboration have found 75 lenses in 1.7 years with daily observations of 6-13 million stars

'An observational program to detect and study Massive Compact Halo Objects (MACHO)

Microlensing By Star **With** Planet
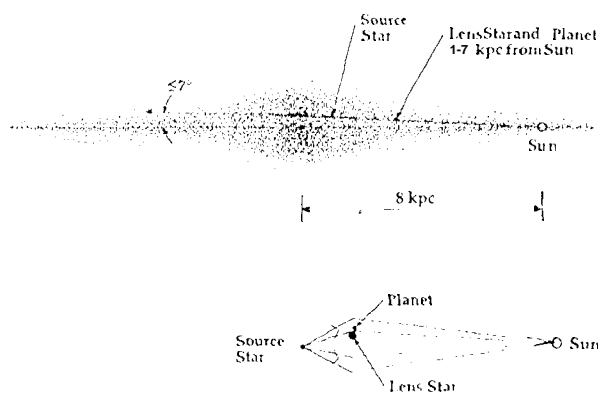
Example of a Gravitational Microlensing Event (MACHO)
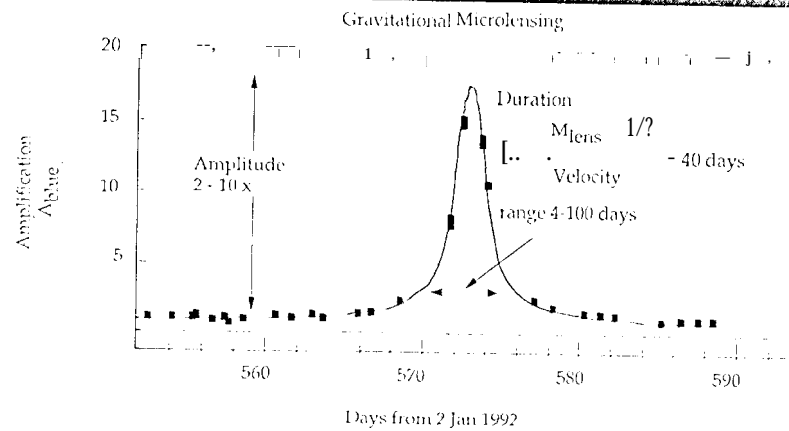
Gravitational Microlensing

Amplitude
2 - 10 x

Duration
M_{lens} 1/?
[.. . - 40 days
Velocity
range 4-100 days

Amplification A_{blue}

Days from 2 Jan 1992

From Alcock et al., 1995

Theoretical Model of Lens **Star** Amplification
$(0.3\ M_{sun})$ Lens Star at 6 kpc

Amplification by
planet in lensing zone

10 Earth-mass planet

1 Earth-mass planet

Amplification

Lensing by star

Days

From Bennett and Rhie, 1995

Lensing Zone

From Gould and Loeb, 1995

A **Possible** Microlensing **Observing Program**
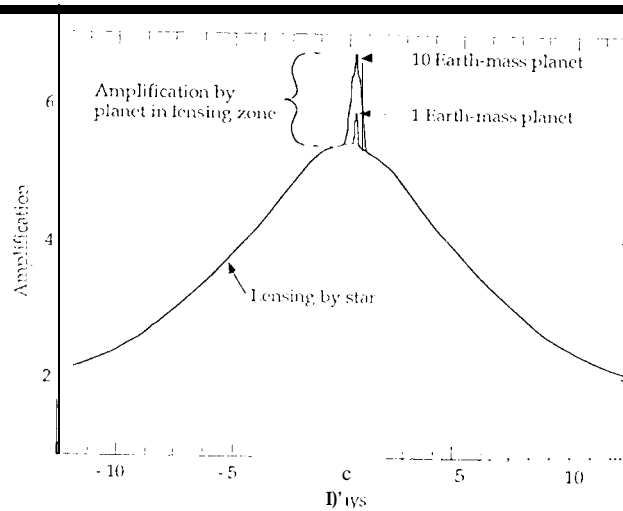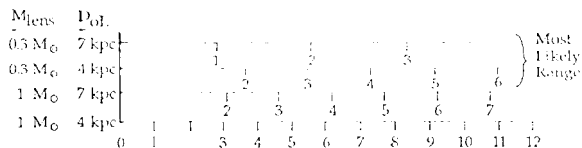
◇ Three part observing program

1. Survey 35 million bulge stars every few nights with southern 2-m telescope and CCDs across 2 degree field (expect 350 lenses/yr)

2. Measure brightness of lensed stars to 1%, every 1-3 hours, expect 70 stars lensed at any instant

3. Intensive measurements of events which deviate from smooth, single lens curves

◇ **Results** of simulated 10 yr observing program

- Assumptions:
  - Assume each star has one planet at random location in lensing zone
  - With four 2-m telescopes will detect
    - 35 Earth-mass planets, or
    - 140 Uranus-mass planets, or
    - 670 Jupiter-mass planets

Direct Detection: Optical Imaging

- ◇ Unresolved images of light from several planets per star
- ◇ Repeat observations will show:
  - • Motion of planets orbiting star
  - • Planetary system properties
    - - Distribution of planets with distance from star
    - - Inclinations and eccentricities of orbits
  - • Unravel radial velocity results
- ◇ Sun and Jupiter at 10 pc:
  - • Contrast in visible light ~10^9
  - • Angular separation 0.5 arcsec
- ◇ Three approaches
  - • HST (Adaptive Optics Coronagraph)
  - • Balloon (Coronagraphic imaging telescope)
  - • Ground-based adaptive optics
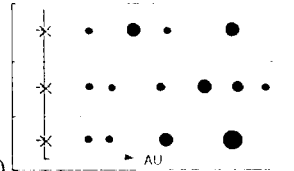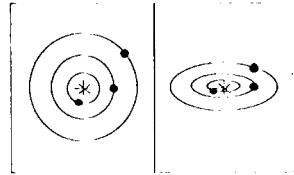
Direct Detection: Ground-Based **Adaptive Optics**

- ◇ **Principle of** AO
  - • AO servo system corrects wavefront aberration of brigh stars and any planets in surrounding field
  - • AO has achieved diffraction limit of <0.2″ on 3-m telescopes
- ◇ Problem: Astronomical AO with .-300 actuators does not suppress star halo sufficiently for planet detection
- ◇ Solution: Fine scale (5 cm) correction at high speed (2 kHz) reduces star halo by 100X. Requires bright stars

Normal astronomical adaptive optics
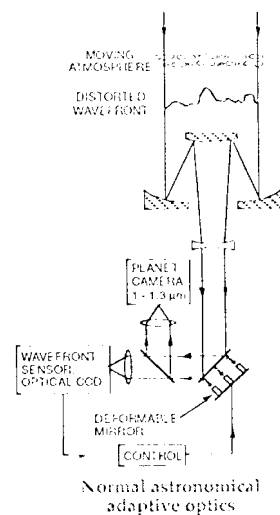
Suppression of Starlight Halo with Adaptive Optics

Intensity

1

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-10}

Seeing Profile

-2   -1   -0   1   2

arcseconds

Normal Adaptive Optics (AO)

Normal AO + Coronagraph

High Resolution AO + Coronagraph
Speckle Noise Level (500 µsec frame)

Planet at 10^{-9} Star (5σ)
Noise Average After 5 hours
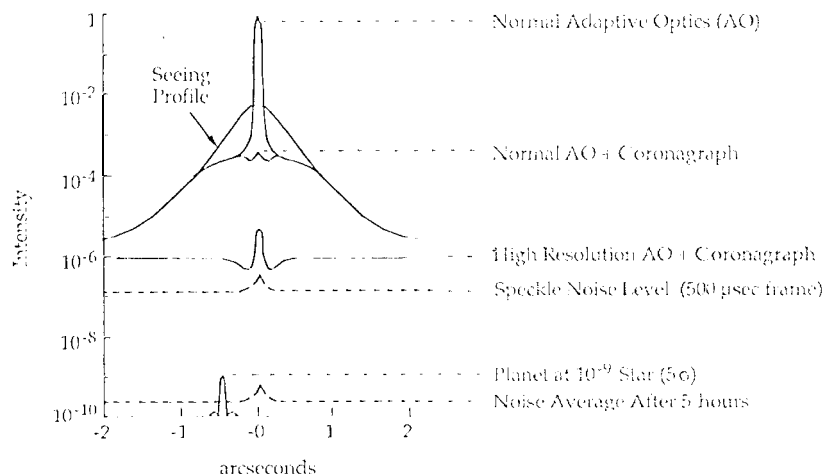
Advanced AO Technology

◇ Technology challenges for implementation:
- Lower cost, deformable mirror with 400 fast-acting elements/m²
- Larger format CCD wavefront sensor with improved noise and speed performance
- New device for adaptive correction of intensity as well as phase errors

◇ Control of systematic errors so photon noise dominates and averages out in long exposures
- Develop servo with clean predictable performance
- Develop interferometric imaging to take advantage of interference signature

Program for Development, Survey and Follow Up

◇ Verify concepts, technology and calibration at Air Force Starfire Optical Range testbed

◇ Build instrument to attain 10^{-9} goal and search ~30 stars

◇ Approach ground-based limit with interferometer using two large telescopes

- Uranus-like planets at 5 AU
- Jupiter-like planets around 100 stars
- Potential for simple spectroscopy (methane)
- AO will be required for all future large-aperture imaging systems (ground and space)

Simulation of Super AO Image of Solar System

Simulation for 5-hour exposure with 6.5-m telescope of a solar system twin at 8 pc. Jupiter stands out, 5σ above the noise background, at 2 "o'clock" position and 0.6 arcsec from the (blocked) central star.
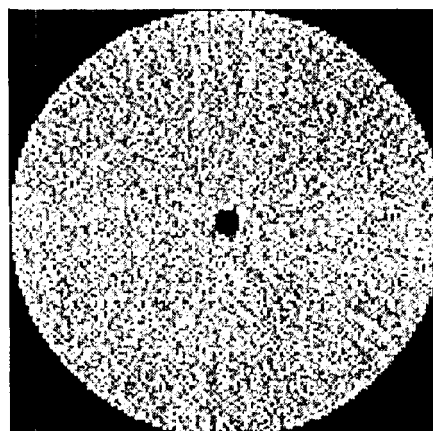
From Stahl and Sanda, 1995

Young Stellar Objects

◇ Where and how are planets made?
  - Forming planets will be easier to detect: larger, hotter
◇ Which stars have disks which make planets?
  - How does disk type depend on star type?
  - Which disks form ice and gas giant planets?
◇ A possible science program:
  - Upgrade mm/sub-mm interferometers to 0.1 arcsec resolution
    - Detection of condensing planets, rings and kinematics of gas
  - 10-micron direct camera for large, low emissivity telescope
    - Luminosity of YSO disks, gaps made by planets, detect hot, young planets
  - High resolution (R= 10^5) IR spectrograph
    - Absorption lines in cool 100K disk gas where planets form
  - Large telescope nulled interferometer with AO
    - Image exo-zodiacal clouds, and direct detection of planets

Debris Disks

◇ Debris disks replenished by colliding comets and asteroids
  - IRAS found many stars with >100 times solar system zodiacal flux
  - Solar zodiacal is 300 times brighter than Earth at 10 µm
  - Stars with low zodiacal are easier for Space IR Interferometer (less zodiacal flux -> less angular resolution, smaller mirrors, shorter integrations)
◇ Possible program: Large telescope (LBT, Keck), low emissivity, nulling interferometer
  - Ground-based 10 µm observation of debris disks around 1000 local stars
    - Direct resolved measurement at few AU (SIRTF needs a model)
    - Interferometry with conventional AO would detect solar zodiacal at <15 pc in <1 hr

Ground Telescope Facilities

◇ **NASA acquired 1/6th of Keck Observatory with the key objective of finding planets**
  - Use large majority of the time for ExNPS observations
  - Select ExNPS instruments by peer review

◇ **Use other large telescopes when:**
  - More efficient
  - Additional telescope time is needed
  - Complex on-site development required
  - For southern sky

◇ **Smaller telescopes needed for:**
  - Bright star radial velocities (one 2-m telescope)
  - Microlensing (four 2-m telescopes)
  - Stellar properties (one 2-m telescope)

Illustrative Large Telescope Program

Program (Start 1996)	Nights/yr	Years
Velocities of 200 stars for Jupiter-mass planets	35	1-10
Astrometry of 50 stars for Uranus-mass planets	35	1-5
Microlensing stars (AO images and spectra)	5	1-10
YSO disks, hot young planets	5	1-10
Direct detection of Jupiters (Advanced AO)	15	2-5
Direct detection of Jupiters (AO on 2-aperture intef.)	2×15	6-10
Exo-zodiacal flux maps (nulled images on two large telescopes)	2×5	6-7
YSO disk absorption	5	7-8
Total	75-95 nights/year (scaled to 10 m)	

New advanced instruments: astrometric camera, 10-35 μm camera, advanced AO, 2-aperture interferometer, IR Echelle spectrograph

Enhanced Theory Program

◇ Understanding of early results and discoveries requires a much stronger theory program with about three times more people

◇ Topics:

- Star and planet formation
- Disk structure, evolution, lifetime
- Stability of stellar spectra for radial velocities
- Stability of stellar images for astrometry
- Interpretation of microlensing results
- Understanding connections between ExNPS observations
  - Can we assume that terrestrial planets exist when we see ice giants?
  - Does strong zodiacal light mean planets are present?
  - Does absence of inner zodiacal light mean giant planets are present and removed the dust?

Key Decisions in 5 Years


```
┌────────────────────┐
│ What is maximum    │
│ common planet mass?│
└────────────────────┘
```

What is maximum common planet mass?

→ Radial velocities / Direct images — Jupiter → Solar system is common

→ Astrometry — Uranus

→ Microlensing — Earth

→ Improve theory of YSO disks → planets

No planets detected

Evaluation: upgrade techniques, or augment with other methods, eg. photometry
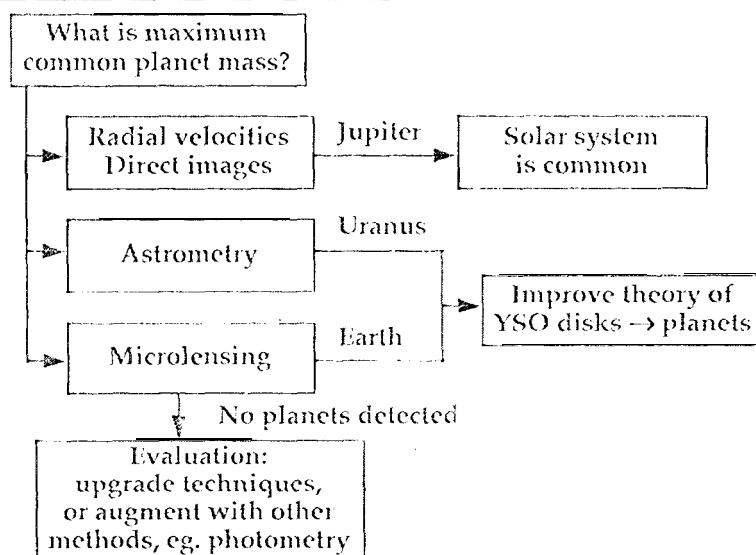
Supporting Space Missions

Charles Beichman
Jet Propulsion Laboratory

ExNPS Needs Supporting Space Missions

- ❖ Near term (10 years) missions will lay scientific and technical foundation for the ExNPS interferometer
- ❖ Characterization of exo-zodiacal dust clouds
  - ISO/SIRTF
  - Exo-zodiacal mapper
    - complements glc)uncl-based interferometer
  - Hubble Space Telescope/balloon coronagraph
- ❖ Astrometric detection of planets
  - Space mission (AIM) confirms and extends ground-based results to below Uranus mass
- ❖ Direct detection of giant planets
  - Hubble Space Telescope/balloon coronagraph
    - complements grcmnd-based Adaptive Optics

ExNPS Needs **Supporting Space Missions** (cont'd)

⬧ Characterization of **our zodiacal** dustcloud
- Zodiacal **brightness at** 3-5 AU dictates ExNPS orbit
- **Understand** anisotropics **in** zodiacal **cloud**
- o Mission at **3-5 AU to** test deep space techniques

⬧ **Science missions** demonstrate critical **technologies**
- o Cryogenic optics (S11<3'1')
- Passive **cooling** to 35 **K al** 3-5 **AU** (SIRTF)
- Interferometry and nulling (AIM)
- Deployable structures **(Al M)**

Characterization of Exo-Zodiacal **Dust** Clouds

⬧ K nowledge of exo-zodiacal **emission critical**
- Exo-zodiacal emission makes photon noise
  - Impacts telescope collecting area
- Exo-zodiacal **emission** swamps planet signal
  Impacts interferometer baseline
- Exo-zodiacal structures masquerade as planets
  Impacts interferometer baseline

Characterization of Exo-Zodiacal Dust Clouds (cont'd)

❖ Distinguish two types of exo-zodiacal cloud s
- Outer (Kuiper-belt) cloud
  - Vega, β Pictoris disks discovered by IRAS
  - 20% of main sequence stars
  - R>50 AU, T <100K
  - Optical depth, $\tau \sim 10^{-3}$ to 10^{-5}
- Inner Cloud
  - Only β Pictoris disk measured from ground
  - R<50 AU, T>200 K
  - Optical depth, $\tau \sim 10^{-3}$ (10^4 brighter than our solar system!)
    - Sharp discontinuity between inner and outer cloud
  - Cometary dust spectrum

❖ Theory links inner and outer cloud s
- Is inner cloud cleared by planets?
- How does material of outer cloud feed inner cloud?

Disk Optical Depth: Solar System with β Pictoris Jump

Distance from star, AU
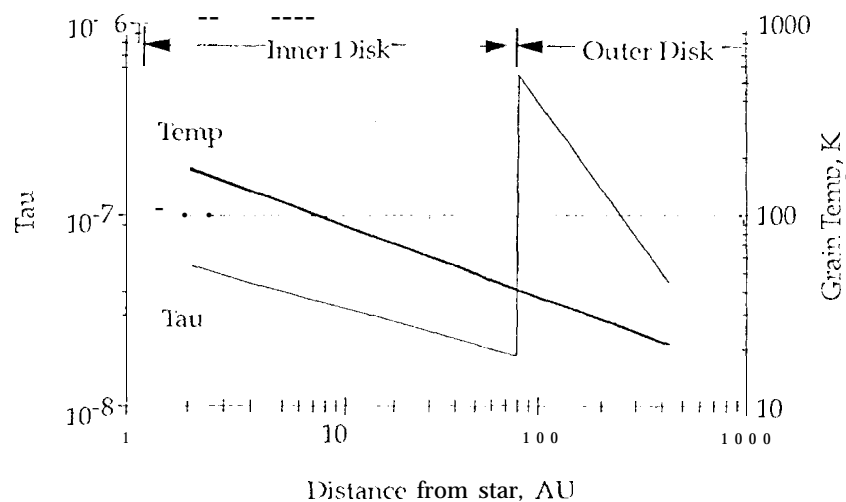
Optical Depth of Outer Disks
(from 1 I{ AS)

What 1S0 and SIRTF Can Do
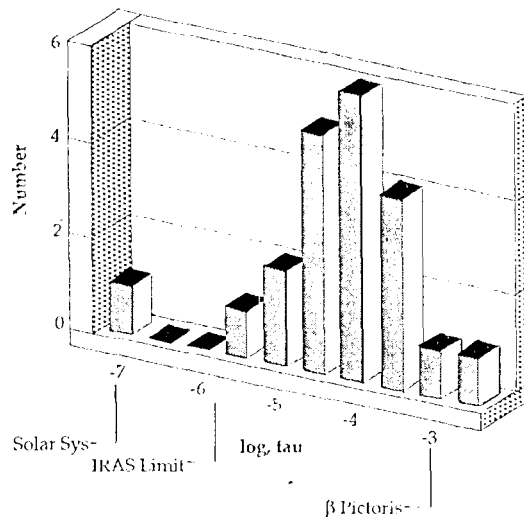
- ISO/SIRTF will probe cold, outer disks
- ISO will **reach** 10-100x solar system **dust level**
- SIRTF **may reach** solar **system dust** level
  - Better resolution than ISO
  - Much better detectors (40 µm BIBs, 60 µm arrays)
  - Critical spectroscopic information
- SIRTF **will survey** nearby stars **to solar system** levels **(>50 AU)**
- SIRTF could search **for outer** planets **of nearest stars**
  - 2-5 Jupiter mass planets orbiting >20 AU of star within 5 pc
  - SIRTF could detect free-flyins, young Jupiters to 200 pc

Detection of Exo-Zodiacal Emission
SIRTF at 60μm (10 pc, 1 sun=1)

—— · · Star brightness in **focal** plane
— Sensitivity after star subtraction
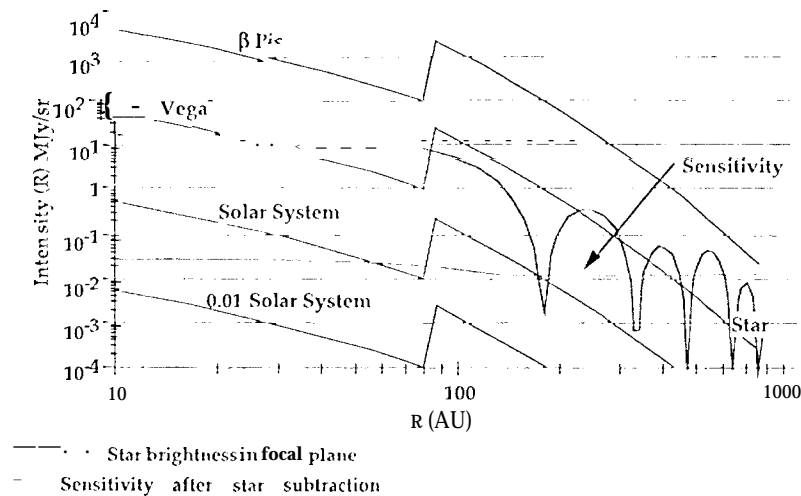
What SIRTF and 1S0 Won't Do

- ⬥ Probing the inner **zodiacal clouds is** difficult for **small** telescopes
  - Stellar diffraction obscures disks
  - Can't probe within 10-30 AU of star
- ⬥ ISO will do little on emission from inner disks
  - Small detector arrays with many anomalies
  - May study closest stars with most massive disks (β Pic)
- ⬥ SIRTF will do better on inner disks, but resolution challenged
  - Study down to 100x Solar System dust level
  - Simple coronagraph could help reject stellar light
- ⬥ Theory plus observations of massive, closest disks will help extrapolation

Technological Benefits of SIRTF

- ◆ Demonstration of high **performance $200 µm arrays**
- ◆ Lightweight, 1-m **class optics**
  - Diffraction limited >6 µm
- ◆ Radiatively cooled **optics and structures**
- ◆ Exploits advantages **(engineering** and **operations)** of heliocentric orbit
- ◆ "Faster, **better,** cheaper" **reduces** cost **by ×4**
  - Demonstrate new ways of doing business
- ◆ Important precursor **for Space** IR Interferometer

Probing the Inner Zodiacal Cloud

- ◆ **Need to measure** $\tau \sim 1 IO\text{-}3$ (β Pic) to 10^{-7} **(solar system)**
  - 'T'-200-300 K, R~1-50 AU
- ◆ Large ground-based telescopes (Keck, Gemini, MMT)
  - Could map disks 10 100x solar system dust level
- ◆ Ground-based interferometers
  - Could study systems with solar system dust levels
  - LBT, 2- Kecks operating as 10 µm nulling interferometer
- ◆ Exo-zodiacal **mapper**
  - Could **map inner 1-5 AU to 0.01-1 solar** system dust **levels**
  - 'Two 0.5-m mirrors separated by 20 meters operating **as** nulling **interferometer**
  - Full **y cryogenic** system in J HEO/L-2 orbit
  - Best **test of science and technology of** ExNPS

Detection of Exo-Zodiacal Emission
Ground-Based Interferometer* at 10μm (10 pc, Lsun=1)

- - - - - - - Star **brightness** in focal plane
- **Sensitivity** after star **Subtraction**

*Two 8-m apertures
50-m baseline
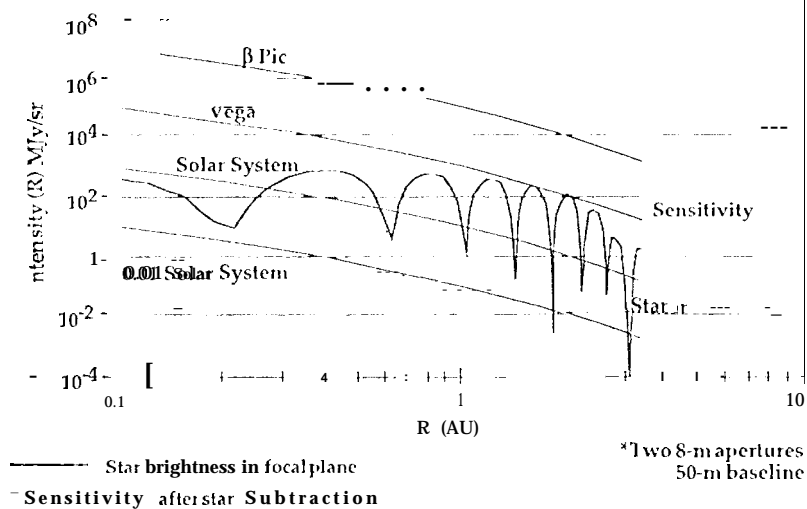
Detection of Exe-Zodiacal Emission
Exo-Zodiacal Mapper at 10μm (10 pc, Lsun=1)

—————— Star brightness in **focal plane**
—————— Sensitivity after **star subtraction**
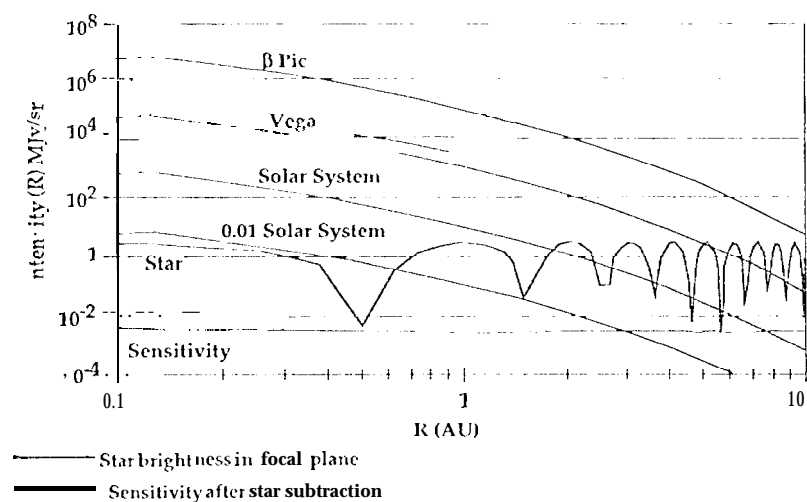
Role of Space Astrometry in ExNPS

◆ Ground-based accuracy (7-10 μas) adequate
  for Uranus
  - Ground or space astrometry can find ~Uranus-mass planets
  - But ground-based program can be started now
    - If it can be done from the ground,
      it will be done from the ground
      before a space mission is launched

◆ Need better accuracy to detect masses below Uranus
  - Space better for survey to 0.25 × Uranus
  - Space essential for survey to find Earths

Role of **Space** Astrometry in ExNPS
(Cent'd)

◆ Astromeic **accuracy and the detection** of **planets**

Baseline (m)	2	6	2(I	60
Accuracy (μas)	2	0.6	0.2	0.06
# Earths	- 5	~25	~100	-1500
# **Uranus'**	1800	3500*	3500*	3500*

*Entire Gliese Catalog

Astrometric Interferometric Mission (Al M)

◇ **AIM presently** planned for wide-field **2-5** µas astrometry

- **AIM** will confirm and extend ~,mund-based astrometry
- Measure sub-Uranus-masses with 5-10 year **lifetime**
- Might **measure 1-5** nearby **stars** for Earths
- Could detect 1000's **of planets**
  - If **systems** are **common:** taxonomy
  - If **systems** rare: good bounds
    - If systems very rare: valid negative result

◇ **Al M will demonstrate** space interferometry

- Precision structures
- Vibration isolation
- Laser metrology, etc.

Astrometric Interferometric Mission (AIM) (Cent'd)

◇ Upgraded AIM could survey **for** Earth-mass wobbles

- 10-100 improvement over **Al M,** < **0.5 pas**
  - Could detect 10's of Earth-mass planets
- Problems include "star noise"
  - Stochastic differences between centers of light and mass.
  - For Sun, noise is <1% of Jupiter signature.
  - Power spectrum of star noise will help unravel signals

◇ Could have strong **technical linkage** to Space IR Interferometer

- Deployed structure
- Nulling system

Mapping Our Own Zodiacal Dust Cloud

◆ Solar system zodiacal emission critical for ExNPS
  - Contributes noise
  - 10 μm zodiacal emission drops by x30 al 3 AU, x150 at 5 AU
  - 1.5-m telescope at 5 AU is equivalent to 6-111 telescope at 1 AU
◆ COBE, IRAS mapped zodiacal cloud from 1 AU
  - Models not sensitive to density falloff beyond a few AU
      Brightness at 3-5 AU not accurately known
  - Anisotropies (I-IO%) suggested by IRAS, COBE, Galileo
      - Could masquerade as planet when seen from afar!
◆ Inexpensive **mission** (<**$50 M**) could **travel** beyond
  3 AU **for in-situ measurements**

Modeled Solar System Zodiacal Brightness
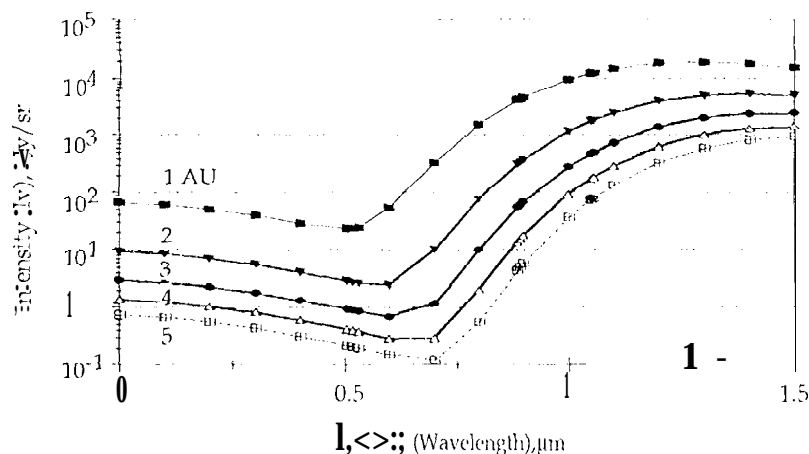
Visible Light Coronagraphs

- ◆ HST coronagraph requires sophisticated optical system
  - Could detect **10-100** Jupiters, image debris disks
    - Apodizing pupil stop, spherical aberration correction
    - 40x40 element deformable mirror (small stroke)
    - High spatial frequency wavefront correction
  - **Astrophysics** potential
    - QSO host galaxies, protostellar disks (near-IR capability)
  - Challenging schedule for 2002 Launch
  - Need to plan Announcement of Opportunity NOW
  - Test of NASA commitment to new ways of doing business

Visible Light Coronagraphs
Direct Imaging Using HST
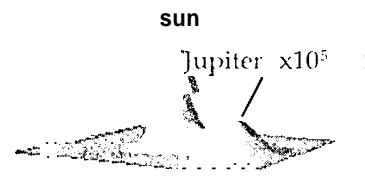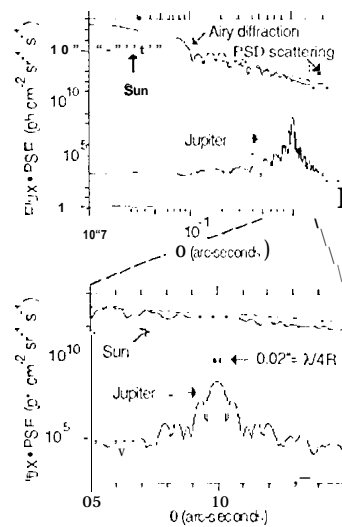
- ◆ Jupiter and the Sun at 5pc distance
  - Jupiter: $m_v = 28$
- ◆ 10% optical bandwidth: 47.50-5250A
- ◆ Based on photon statistics only, WFPC detection would take 39 days!
- ◆ Adaptive Optics coronagraph can suppress starlight and detect Jupiters around nearest stars in a few hours

Visible Light Coronagraphs (cont'd)

- ◆ **Balloon telescope** offers alternative **approach**
    - ● Optimized **1.5-m off-axis** telescope with coronagraph
        - Slow, high finesse Adaptive Optics and/or scattering compensation
    - ● 16 hours/star to measure up to 70 stars
    - ● Long duration balloon flights to 30-40 km
    - ● Back-up if 11 ST cannot be ready in time
- ◆ Technology demonstration for precision wavefront **control**
    - ● Key technology for large visible ight telescopes

Road Map and
Summary of Discoveries

Charles Elachi
Jet Propulsion 1 aboratory

Top Level Draft Road Map

- Interstellar probes?
- Multi-pixel imaging?
- High resolution Spectroscopy?

- Images of 150-200 planetary systems
- Spectroscopic characteristics
  - Biology
  - Water
  - Atmosphere

- Are terrestrial planets common?
- Detection of giant planets
- Is our "dust cloud" common or unusually small
- Are planetary systems common

IR Interferometer
- 50-100m baseline
- 1-2m size telescopes
- 3-5 AU

Ground Observations

Technology Demos

Planned Flight Mission

Imaging
Astrometry
Radial velocity
Micro lensing

- Space Boom Technology Experiment
- Characterization of local zodiacal
- Ground technology demos

- AIM (2003)
- HST Coronograph (2002)
- SIRTF (2001)

Time

now

Long Term Horizon

Large Aperture Telescopes?　　Multi S/C Interferometer?　　Interstellar Probe?
High resolution　　　　　　　　Multi-pixel imaging　　　　　　Close-up imaging
Spectroscopy

Few hundred systems imaged
and spectroscopically
characterized

Science/Observation Road Map

- Family portrait
- Direct imaging of systems
- Spectral Characterization

Space IR Interferometer/Spectrometer

Local zodiacal
intensity mapper
3-5 AU

Exo-zodiacal disk
mapper

Ground

- Direct detection of Jupiter/
  Neptune size planets (Ground/
  Telescopes/Balloons/HST inst.)

- Indirect detection of large
  planets (Ground Astrometry
  and Radial Velocity)

- Disk characterization
  (interferometer)

- Statistics of Terrestrial planets
  (Micro-lensing)

- Exo-zodiacal disk
  characterization

  SIRTF

- Indirect detection of
  giant planets ≥ Uranus
- Mass of giant planets

  AIM

1

Technology Road Map

```
                    ┌─────────────────────────┐
                    │    Space Infrared       │
                    │ Interferometer/Spectrometer │
                    └─────────────────────────┘
                       ↗      ↑    ↖      ↖
```

Deeperspacce telescope operation - Passive cooling to 60K Cryogenicic telescope	Spatical&inteferometric imaging - Metrology - Pointing - Nulling	- Light weight telescope Nulbling techniques - Metrology tests Palomar Testbed Interferometer(PTI)	Dynamiu behaviorr of large (>50m)boomin cold environment
↑ SIRTF	↑ AIM	↑ Ground Testbed	↑ Technology i Orbit 1....

Different Methods of Planet Characterization

Chart showing detection methods across Saturn/Jupiter Mass, Uranus/Neptune Mass, and Earth Mass:

- **Ground Indirect**: Radial Velocity, Astrometry (Palomar PTI, New Interferometer), Microlensing (Statistical Detections)
- **Ground Direct**: AO, MI1OO,1 "1 Clc.cope
- **Space Indirect**: AIM (7,,1 20 m)
- **Space Direct**: HST Coronagraph, Space Interferometry

ExNPS Overall Road Map

Exo-zodiacal Characterization

inner Cloud
<1 AU

Middle Cloud
5 AU

Ground Interferometer
or
Exo-zodiacal Mapper

Outer Cloud
> 10 AU

ISO   SIRTF

100 x   10x   1 x
Solar System Solar System Solar System

Some Key Decision Points

◇ I f after 5 **years** of ground **observation** no **convincing
examples** of **planetary systems are detected, then a
photometric occultation mission might be considered
as a new element in the road map**

◇ **If exo-zodiacal light in neighboring systems is far
larger than our own, then the Space IR
Interferometer design will require significant change
(spectral coverage, baseline, aperture size)**

◇ **A better understanding of our own zodiacal light will
have a measurable impact on the Space IR
interferometer mission design (orbit, aperture size)**

Discovery/Knowledge Timeline

♦ **Phase 1: Ground Based and Precursor Space Mission**

Are planets **common** occurrences in the galaxy? How abundant are Jupiter-class versus Neptune-class versus Earth-class planets?

- Microlensing

Are Jupiter-class or Neptune-class planets common around stars near the sun?

Ground-based (AO, radial velocity, astrometry); AIM

What is the strength of the zodiacal glare in others systems? Is it related to the presence or type of planetary system?

ISO/SIRTF/ground interferometer

How does our own zodiacal glare fall off with distance from the son? How far must we go to move out of the infrared glare?

Zodiacal mission/modeling

What is the mass of planets around neighboring stars?

AIM/Ground observations

Discovery/Knowledge Timeline

♦ **Phase 11: Space IR Interferometer**

Does the star possess planets in the habitable zone?

Infrared interferometer

How many stars in the solar neighborhood possess planets, and what sorts of orbits are they in?

Infrared interferometer

Does the planet possess an atmosphere?

IR interferometer spectroscopy of carbon dioxide

Is the planet potentially capable of supporting life?

- IR interferometer spectroscopy of water

Are there photosynthetic forms of life widespread on the planet?

IR interferometer spectroscopy of ozone (later methane by high-resolution spectroscopy)

Discovery/Knowledge Timeline (cent'cl)

◆ Phase III: Long Term 1 Iorizon

What **is** the size of **the planet? 1** Does the **planet** have moons?
  lew-pixel imaging

Is the surface mostly land, liquid water, or ice?
- Multi-pixel imaging

implications of the Exploration of Neighboring Planetary Systems

Alan Dressler

Carnegie **observatory** -- Pasadena

The HST & Beyond Committee

◆ Chartered **by AURA and** the **Space Telescope** Institute **Council to consider** possible **successors to** the Hubble **Space Telescope**

◆ Two key scientific **goals** for **space astronomy** in the coming **decades:**

- **(1)** the direct study of the birth and evolution of galaxies like the Milky Way
- (2) the detection of E,arlh-like planets and the search for evidence of life on them

◆ **Recommendations to NASA:**

- Extend the life of the Hubble Space Telescope beyond 200.5
- Develop and construct a cooled space observatory with 4-meter aperture, optimized for wavelengths 1-5 microns
- Develop the capability for space interferometry

The Future

♦ Space interferometry:
- Microarcsecond astrometric observations for fundamental distances to stars within our galaxy and its neighbors
- imaging with milliarcsecond resolution for the study of quasars, stellar surfaces, exotic systems like SS443, stellar **population** in nearby galaxies...

♦ The **legacy. of** ExNPS:
- **An** extended **search** for more Earths!
- Higher spectral **resolution studies of** the **atmospheres of** the planets **in** the **habitable** zone --- exploring the **conditions for life**
- **}ligh-resolution pictures of** Earth-like planets, showing topography and atmospheric features
- **interstellar** probes **sent to** our most captivating neighbors

Conclusions and Recommendations

Charles Elachi
Jet Propulsion Laboratory

Conclusions

* The exploration **and characterization** of **neighboring planetary systems including** Earth-like planets **is feasible and within our** expected **technological capability** in **the** next **decade.** There **are** no **technological "show** stoppers", **but** there **are significant engineering** challenges
* An **aggressive** ground-based **observation** program will allow **the detection of** Jupiter/Saturn/Uranus- **size Planets** and **is** expected to provide **statistics for** Earth-size planets
* **Planned** space **missions** will allow **characterization of disk properties** (SIRTF) and provide indirect **detection of** large planets (AIM)

Conclusions (cent'd)

⬥ Planned **missions** and laboratory testbeds **could demonstrate** the **vast majority of** the key **technologies for the** needed infrared space interferometer/ **spectrometer**

⬥ **An infrared** space interferometer/spectrometer **will provide**

- Direct observation (family portrait) of the neighboring 150-200 planetary systems
- Spectral characterization of individual planets
- Capability to search for habitable (Earth-like?) planets

Draft Recommendations to NASA

⬥ Initiate a focused and **aggressive ground-based program**

- Exploit greatly **increased** potential from ground
    - New generation of large aperture telescopes
    - New methods to beat atmospheric distortion (direct imaging and astrometry)
    - New method for indirect detection (microlensing)

- Capitalize cm NASA investment in Keck, Palomar interferometer and IRTF

- Exploit new techniques with common grm]nri/space technology component

    Direct imaging technology (Adaptive Optics, Balloon telescope, 11S1 coronagraph)

    1,ong baseline interferometric astrometry (Palomar testbed, advanced interferometer)

    Long baseline, large-a perture interferometric imaging for characterizing inner zodiacal clouds

Draft Recommendations to NASA (cont'd)

- ❖ Initiate a focused and **aggressive** ground-based program (cont'd)
  - Support new 2-m class telescopes (microlensing, radial velocity)
  - Define desired configuration of HST coronagraph
  - Encourage competition and innovation in all aspects
    - Broad opportunities, peer review
    - Utilize other ground facilities if they provide unique capabilities or are cost effective
  - Enhance ongoing Origins program
    - Support broad-based research covering other parts of the spectra (millimeter, submillimeter, etc.)
    - Support modeling and lab efforts to provide better insight in interpreting observational data

Draft Recommendations to NASA (cont'd)

- ❖ **initiate concept studies for Space interferometer** to **specifically identify** needed **technological/ engineering development**
  - involve universities and industry
- ❖ Conduct an **aggressive technology** development **program**
  - Form an oversight panel of technologists/engineers to regularly review technology activity
  - Expand participation of universities/industry in JPL/NASA interferometry technology
  - Define and conduct needed technology development
- ❖ Conduct **technology flight mission to characterize full-size metering structure in** space
- ❖ Invest in new breakthrough **technologies that** might enable **different measurement** techniques

Draft Recommendations to NASA (cent'cl)

- ◆ Conduct phase A/B for **AIM** with specific ExNPS technology needs incorporated for phase C/D in 2000 and launch **in 2003**
- ◆ Develop an integrated ExNPS/AIM/post-HST strategy **for** the next decade
    - Form an integrated S W G
    - ("ordinate technology development with 11 S'1" Follow-on needs
- ◆ **Acquire needed data from** near term **missions**
    - ISO/SIRTF
- ◆ Define HST coronagraph
- ◆ Develop **strategy** for outreach, **education,** and **workshops on public interest**
- ◆ Explore **international** partnership
    - Horizon **2000** plus (ESA), Russia, Japan